Downscaled GCM Trends in Projected Air and Water Temperature to 2100 Due To Climate Variation in Six Sockeye Salmon Watersheds

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DOWNSCALED GCM TRENDS IN PROJECTED AIR AND WATER TEMPERATURE TO 2100 DUE TO CLIMATE VARIATION IN SIX SOCKEYE WATERSHEDS

by

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ABSTRACT

Stiff, H. W., K. D. Hyatt, M. M. Stockwell and A. J. Cannon. 2018. Downscaled GCM Trends in Projected Air and Water Temperature to 2100 Due To Climate Variation in Six Sockeye Watersheds. Can. Tech. Rep. Fish. Aquat. Sci. 3259: vi + 83 p.

Freshwater temperatures in British Columbia are expected to rise over the 21st century due to climate change. Water temperatures exceeding 19 °C can impede or impact the health of adult Sockeye Salmon migrants in freshwater. To understand the vulnerability of key Sockeye stocks to potential changes during adult salmon migration in freshwater habitat through the next century, daily minimum and maximum air temperature time-series from Global Climate Model (GCM) projections, downscaled to regional locations associated with six Sockeye stocks in British Columbia, were downloaded from the University of Victoria's Pacific Climate Impacts Consortium data portal. Downscaled bias-corrected outputs were obtained for ten GCMs and two Representative Concentration Pathway (RCP) trajectories (4.5 and 8.5) and translated into daily mean water temperature based on site-specific air-to-water temperature models for a reference period (1971-2000) and three 30-year time-periods (2011-2040, 2041-2070 and 2071-2100). Two salmon vulnerability indices were derived from the water temperature time-series for each time-period, RCP, and month of active migration (June-September): (i) average frequency of dates per migratory period (in days); and (ii) average duration (in continuous days) – when mean daily water temperature exceeded the biological threshold (19 °C) relevant to migrant Sockeye.

Site-specific downscaled GCM data indicated that air temperatures in six Sockeye watersheds are projected to rise during peak migration months (July-September). Air temperature increases over the 21st century ranged from a minimum of 2-3 °C to a maximum of 4-5 °C, depending on RCP scenario. These translated into maximum mean water temperatures of 17-18 °C for central and northern watersheds, including Tahltan, Meziadin, Babine, and Docee, which were characterized by cool baseline temperatures (13-16 °C) during the reference period. These results indicate neutral or negligible thermal disruption for adult freshwater migrants for central and northern Sockeye index stocks. In southern watersheds, water temperatures were projected to reach 21-22 °C in Somass River and 22-24 °C in Sproat River, and exceed Sockeye thermal tolerance levels for uninterrupted adult migration (19 °C) for >80% of peak migration months by the 2020s in Sproat River and by the 2050s in Somass River. The middle 50th percentile of all model outcomes indicated a potential range of 75-96 days per year presenting combinations of elevated thermal stress and thermal barriers to upstream migration in the Somass by the 2050s, equivalent to 62-79% of the 122-day migratory period between June to September. Mean duration of Somass hyper-thermal events ranged from 27 to 33 days by the 2050s, depending on RCP. These results point to a high likelihood of significant and repeated disruptions to freshwater migration for Somass and Sproat stocks via frequent and lengthy (multi-week to month-long) delays in migration, as early as the 2020s, which do not augur well for sustainable production of Somass Sockeye salmon.

RÉSUMÉ

Stiff, H. W., K. D. Hyatt, M. M. Stockwell, et A. J. Cannon. 2018. Downscaled GCM Trends in Projected Air and Water Temperature to 2100 Due To Climate Variation in Six Sockeye Watersheds. Rapport technique canadien des sciences halieutiques et aquatiques, 3259: vi + 83 p.

Les températures des eaux douces en Colombie-Britannique devraient afficher une hausse au cours du 21^{e} siècle en raison du changement climatique. Des températures de l'eau dépassant 19 °C peuvent compromettre la santé des saumons rouges adultes migrant en eau douce ou avoir un impact sur celle-ci. Pour comprendre la vulnérabilité des principaux stocks de saumons rouges face aux changements potentiels dans l'habitat d'eau douce au cours du 21^{e} siècle, nous avons téléchargé des séries chronologiques des températures de l'air minimales et maximales quotidiennes utilisées dans les projections du modèle du climat mondial (MCM) et mises à l'échelle des emplacements où l'on trouve six stocks de saumons rouges de la Colombie-Britannique à partir du portail de données du Pacific Climate Impacts Consortium de l'Université de Victoria en vue d'évaluer les changements attendus dans la température de l'eau durant les périodes de migration en eau douce des saumons adultes. Des résultats mis à l'échelle ont été obtenus pour dix MCM et deux trajectoires RCP (Representative Concentration Pathway) (4,5 et 8,5) reposant sur la correction des biais/la méthode de correction des biais utilisée pour la cartographie analogue construite des quantiles et traduits en températures de l'eau moyennes quotidiennes d'après des modèles de la température de l'air et de l'eau propres aux sites pour une période de référence (1971-2000) et trois périodes de 30 ans (2011-2040, 2041-2070 et 2071-2100). Deux indices de la vulnérabilité des saumons ont été dérivés des séries chronologiques de la température de l'eau pour chaque période, scénario RCP et mois de migration active (juin à septembre) : i) la fréquence moyenne des dates par période migratoire (en jours) et ii) la durée moyenne (en jours continus) – lorsque la température de l'eau moyenne quotidienne dépassait le seuil biologique (19 °C) établi pour les saumons en migration.

Les données dérivées des MGM mises à l'échelle de sites particuliers indiquaient que les températures de l'air dans six bassins hydrographiques soutenant des saumons rouges devraient, selon les projections, s'élever durant le pic de la migration (juillet à septembre). Les hausses de la température de l'air au 21^{e} siècle s'échelonnaient entre 2 à 3 °C, au minimum, et 4 à 5 °C, au maximum, selon le scénario RCP. Ces hausses se traduisaient par des températures de l'eau moyennes maximales de 17 à 18 °C pour les bassins hydrographiques du centre et du nord, incluant ceux des rivières Tahltan, Meziadin, Babine et Docee, qui étaient caractérisées par des températures de référence froides (13 à 16 °C) durant la période de référence. D'après ces résultats, les adultes migrant en eau douce pour les stocks indicateurs de saumons rouges du centre et du nord de la région devraient afficher un degré de perturbation thermique neutre ou négligeable. Dans les bassins hydrographiques du sud, on prévoit que les températures de l'eau atteindront 21 à 22 °C dans la rivière Somass et 22 à 24 °C dans la rivière Sproat, et dépasseront les niveaux de tolérance thermique du saumon rouge associés à une migration des adultes non perturbée (19 °C) pour plus de 80 % des mois où la migration atteint son pic d'ici 2020 dans la rivière Sproat et d'ici 2050 dans la rivière Somass. Le 50^{e} percentile (moyenne) de tous les résultats du modèle indiquait que, dans une fourchette allant de 75 à 96 jours par an, on assistait à une combinaison de stress thermique élevé et d'obstacles thermiques à la migration vers l'amont des saumons de la rivière Somass d'ici 2050, ce qui équivaut à 62 à 79 % de la période migratoire de 122 jours entre les mois de juin et de septembre. La durée moyenne des événements hyperthermiques dans la rivière Somass s'échelonnait entre 27 et 33 jours d'ici 2050, selon le scénario RCP. D'après ces résultats, il est très probable que la migration en eau douce des saumons appartenant aux stocks des rivières Somass et Sproat présentera des perturbations importantes et répétées, par l'entremise de retards fréquents et prolongés (allant de plusieurs semaines à un mois) de la migration dès 2020, ce qui n'augure pas bien pour une production durable des saumons rouges dans la rivière Somass.

INTRODUCTION

Within the general category of natural disturbance regimes or events, annual and seasonal variations in freshwater temperature and flow represent the most common factors exerting a major influence over salmon life history outcomes. Climate models project significant changes in regional air temperature along Canada's west coast in the coming decades, which are virtually certain to induce widespread impacts on demographic and behavioural traits of salmonid populations in the region (e.g. Hyatt et al. 2016).

Temperature effects on migrating adult Sockeye (*Oncorhynchus nerka*) have been well documented in many river systems in the Pacific Northwest (Hyatt et al. 2003; Nelitz, Alexander and Wieckowski 2007; Salinger and Anderson 2006). Lethal water temperatures are reported in the range 21-24 °C, and temperatures in excess of 18 °C may negatively affect migration behaviour, cause migration delays, and alter spatial distribution of Sockeye salmon (Cooke et al. 2004; Crossin et al. 2008; Hyatt et al. 2015). Elevated water temperatures may also result in increased parasitism, pathogens and disease, resulting in enroute or pre-spawn mortality (Hinch and Martins 2011). Thermal stress has also been related to secondary effects such as reduced salmon gamete viability and fertilization rates, and decreased egg-to-fry survival rates (Jensen et al. 2004).

Flow extremes, both high and low, can exacerbate elevated water temperature impacts on migrating salmon. High flows coincident with particular features of stream morphology may create location-specific velocity barriers that reduce or prohibit upstream migration for extended periods (Hinch and Bratty 2000; Burnett et al. 2014). High flows may also be energetically-costly to upstream migrants (Hinch and Rand 1998), especially over long migratory distances (Lee et al. 2003). Low flows may facilitate rapid temperature increases and/or impede fish passage at natural barriers and human infrastructures such as fish ladders (Pellett et al. 2015).

Analyses of historical data indicate that significant changes in regional meteorological factors (such as air temperature and precipitation) that directly affect freshwater quantity and quality have already occurred in response to climate change in Canada's Pacific region (e.g. Whitfield and Cannon 2000; Whitfield 2001; Nelitz et al. 2007). Recent investigations in the Pacific Northwest and British Columbia have demonstrated annual air temperature increases of about 0.14 °C (range 0.08-0.23 °C) per decade over the 20th century (Zhang et al. 2000; Mote et al. 2003), an annual warming trend that has intensified to 0.19 °C (range 0.08-0.38 °C) per decade since the 1950s for coastal British Columbia (Bush et al. 2014; PCIC 2013a;b;c).

Regional climate projections based on global climate models (GCMs) point to further intensification of these changes through the 21st century as atmospheric concentrations of 'greenhouse gases' (GHGs) continue to rise (Abdul-Aziz, Mantua and Myers 2011; Littell et al. 2011; IPCC 2013)[1]. In the Pacific Northwest and British Columbia, air temperatures have been projected to increase 1.5 to 3 °C in near-future decades (Mote et al. 2003) with increases of summer temperatures of up to 4 - 5 °C by 2100 (Mote and Salathé 2009) and maximum relative increases of up to 7 °C in autumn and winter seasons (Bush et al. 2013). Even under low emission scenarios, by the middle of the century British Columbia – like the rest of Canada – is anticipated to warm by about 1.5 - 2.5 °C in summer, the season of weakest projected warming (Bush et al. 2013).

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[1] The rate of air temperature change in the long term is highly dependent on the projected rate of GHG emissions generated by society as a whole. However, the emissions trajectory will not be a significant factor in the next few decades due to recent and current GHG contributions already committed to the atmosphere (IPCC 2013). In the near-term (i.e., through the 2040s to 2070s),

Climate analyses also indicate that the magnitude and direction of historical and projected climate variation and change (CVC) exhibit sub-regional specificity because British Columbia is not only large but also topographically-complex (Walker and Sydneysmith 2008; Fleming and Whitfield 2010; Fleming et al. 2016).

On the west coast of Vancouver Island and central coast, temperature increases are projected to be relatively uniform across the seasons, with an annual median warming of 1.4 °C (range 0.8 °C to 2.2 °C) by the 2050s and 2.3 °C (1.2 °C to 3.5 °C) by the 2080s (PCIC 2013b)[2]. By the 2080s, about 60% of summers would be hotter than the warmest 10% of summers in the 20th century (ibid). Along the north coast and southeast Alaska transboundary region, warming is projected to occur at a slightly higher rate, with annual increases of 1.8 °C (range 1.1 °C to 2.5 °C) by the 2050s and 2.6 °C (1.5 °C to 4.3 °C) by the 2080s (PCIC 2013c). In the 2080s, nearly 66% of summers would be hotter than the warmest 10% of summers in the last century (ibid). In the southwest region of mainland British Columbia, including Georgia Strait, summer temperatures were projected to warm slightly more than other seasons, by 2.0 °C (1.4 °C to 2.8 °C) by the 2050s and 3.1 °C (1.9 °C to 5.0 °C) by the 2080s (PCIC 2013a).

As regional air temperatures increase, the physical and seasonal distribution and intensity of precipitation will change, and, in turn, alter freshwater hydrology and thermal regimes in geo-specific ways (Bryant 2009; Zwiers, Schnorbus and Maruszeczka 2011). In the continental climate of the Interior of British Columbia, PCIC projections show that current glaciers will shrink 60-80% in area and volume and some will disappear by 2100 (PCIC 2013d). Nivo-glacial watersheds will shift towards pluvio-glacial, altering the timing and quantity of freshwater supplied to rivers, lakes and the coast, and changing the availability of sediments, organic materials and nutrients in downstream ecosystems (ibid). Along the coast, minimum losses of 50% of glacial area and volume are anticipated for even the lowest emissions scenario (ibid). Nivo-pluvial (snow-melt dominant) watersheds will shift towards pluvial (rainfall-dominant), leading to reductions to both winter snowpack and late summer flows and increases in winter flooding and summer drought, especially in the south (Mantua et al. 2010).

These shifts in thermal and hydrological regimes are expected to stress wild salmon populations to their physiological limits in the Pacific Northwest, southern British Columbia (Mote and Salathé 2009) and the B.C. Interior (Gottesfeld et al. 2002), potentially leading to

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latitude, topography, elevation, and seasonal factors will exert a larger influence over regional temperature trends (IPCC 2013).

[2] The projected change given is the median from an ensemble of 30 GCM projections from the Coupled Model Intercomparison Project Phase 3 (CMIP3). The range, in brackets, is the 10th to 90th percentile of projected changes. Details about the ensemble, known as PCIC30, are given in: Murdock and Spittlehouse (2011).

habitat loss (O'Neal 2002), declines in abundance and, in severe cases, accelerated extinctions (Katz et al. 2013). However, salmonids exist over a wide range of climatic conditions along the Pacific coast, and current cool conditions in northern coastal watersheds may absorb temperature increases of several degrees without significant biological impact or may benefit certain life stages, such as improved growth of juveniles (Beer and Anderson 2013). Individual stocks exhibit life history adaptations in timing of migration, emergence, and residence in freshwater that are often unique to regions and watersheds (Bryant 2009). Since salmon populations also differ in their thermal tolerances, reflecting local or sub-regional adaptation to conditions over their historic evolution (Farrell 2009; Martins et al. 2012), stock-specific responses to climate variation and change impacts are also possible. Thus a species- and stock-specific approach to climate impacts analysis is necessary to understand their biological vulnerabilities (Nelitz et al. 2007; Mauger et al. 2016), which have management and conservation implications (Schindler et al. 2008; Hague and Patterson 2007).

OBJECTIVES

The purpose of this report is to explore the potential impacts of changes in 21st century stream temperatures in freshwater migration corridors at sites of particular relevance to six Sockeye populations ("index stocks") in British Columbia. Spawning grounds for these diverse populations are geographically-distributed across five major drainages and four biogeoclimatic zones.

Retrospective (historical) analyses of climate-related changes in water temperature and discharge have been developed for these sites, covering portions of the 20th century (e.g. Hyatt et al. 2015; Stiff et al. 2015 a,b,c). These analyses used continuous daily records of historical air temperature and discharge from nearby ENVIRONMENT CANADA (EC) meteorological and hydrometric stations. EC records were statistically-combined with local but fragmented stream temperature and water level records to create continuous time-series of daily water temperature and flow estimates. To date, these site-specific, time-series have been used with daily Sockeye Salmon migrant count data to identify species- and stock-specific limiting factors in water temperature and stream flow associated with freshwater migration as a key salmon life-history event (LHE)[3].

A common upper thermal limit that defines a biological impact on adult Sockeye migration in freshwater was drawn from these analyses: daily migration (as a percentage of total annual 'escapement') is generally reduced to insignificant levels (i.e., below the 50th percentile) when estimated daily mean water temperature exceeds 19 °C. This finding is supported by research that links reduced reproductive success and/or mortality with water temperatures in excess of 18-19 °C (Hyatt and Stockwell 2003, Hyatt et al. 2016; Cooke et al. 2004; Crossin et al. 2008; Walthers and Nener 1997)[4]. From this information, two simple exceedance-type exposure indices were derived to document historic climate-induced "salmon vulnerability indicators" for adult Sockeye migrants:

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[3] Spawning, egg incubation, and recruitment life-history-events will extend the analyses.

[4] In essence, the more frequently or extensively water temperatures exceed the threshold, the fewer healthy fish survive to reproduce.

(1) the mean frequency of dates during the adult migration period[5] when daily mean water temperatures exceeded the 19 °C threshold; and:

(2) the mean duration (in days) of continuous dates when the 19 °C threshold was exceeded during the adult migration period.

As these indicators are based on water temperature alone, they may be used to assess the historic to current vulnerability status for this LHE in other Sockeye watersheds where fish migration data may not be available but daily temperature data are available. Furthermore, potential changes in the vulnerability status due to future climate change may be obtained based on daily air temperature projections from readily available-climate model outputs.

For this study, site-specific daily mean water temperature estimates for the 21st century were derived from a wide range of GCM air temperature projections obtained from the University of Victoria's PACIFIC CLIMATE IMPACTS CONSORTIUM data portal (PCIC 2014), which were downscaled to the six watersheds associated with the Sockeye salmon index stocks. Air and water temperature changes and associated salmon vulnerability indices are summarized for the adult freshwater migration phase of each index stock, by migration month, GHG emissions trajectory, and 30-year time block from 2011 - 2100.

STUDY AREA

The Sockeye index stocks in this study occupy a highly varied geographic and climatic range along the north-south axis of BC, from the temperate outer coast watershed of the Somass R. in the south to the subarctic interior watershed of the Stikine and Tahltan rivers in the north (Figure 1; Hyatt et al. 2008; 2016). A complex physiography contributes further variability in climatic conditions over short distances along the east-west axis (Figure 2), as mountain ranges force the majority of the precipitation from coastal storms to fall on the western slopes, leaving the leeward areas 150-200 km inland much drier or even semi-arid (Peel, Finlayson and McMahon 2007). As a result freshwater migration life history events for these six Sockeye stocks occur in three different Köppen climatic regions (Figure 3). These range from *oceanic* for southern and central coast stocks, to variants of *subarctic* for interior and northern stocks, and cover at least four biogeoclimatic zones (Figure 4). Individual stocks may transit multiple climatic zones to reach their natal watersheds. In addition, each Sockeye "system" is uniquely characterized by hydrometric differences in river length, discharge, headwater lake size and altitude (Table 1), which combine with climatology (Figure 5) to influence annual hydrology (Figure 6) and thermography (Figure 7).

Somass and Sproat Rivers

The Somass River drains an area of about 1,426 km² into Alberni Inlet, a 54-km coastal fjord on southwestern Vancouver Island (Figure 1, Figure 2). The Somass watershed consists of three sub-basins with headwater lakes (Figure 8), dominated by the Great Central Lake system, which drains into the Somass via the 20-km Stamp River, and the Sproat Lake system, which drains into the Somass via the 2-km Sproat River.[6] The Somass

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[5] Ranging between June and September, depending on Sockeye stock.

[6] The mean annual discharge (MAD) for the Stamp River is 76 cms. MAD for the Sproat River is 38 cms. A third Somass watershed sub-system, draining into the Stamp River, includes the regulated Ash River system, draining Oshinow and Elsie lakes (MAD 17 cms).

River, formed at the merger of the Stamp and Sproat rivers, has an annual mean flow of 121 cms (Table 1).

The Somass and Sproat watersheds are characterized by an *oceanic* coastal climate[7] – temperate, humid, and characterized by mild winters, warm summers, and long spring and autumn seasons with small seasonal ranges in temperature due to the moderating effects of the Pacific Ocean (Figure 3). The dominant COASTAL WESTERN HEMLOCK biome (Figure 4) gives way to INTERIOR DOUGLAS FIR forests in drier inland areas, and to MOUNTAIN HEMLOCK at higher elevations (PCIC 2013). Precipitation is rainfall-dominated (pluvial)[8] and generally highest in autumn and winter, and lowest in summer (Figure 5), leading to a pluvial hydrologic regime typical of temperate coastal systems (Figure 6). Summer discharge levels (Jul-Aug-Sep) may drop to 60% of MAD in Somass River, and 26% of MAD in the Sproat River (Hyatt et al. 2015).

Due to the complex topography associated with the VANCOUVER ISLAND mountain range, climatic conditions vary widely over short physical distances – mean summer air temperatures generally peak at 14.7 °C on the open coast, and 18.2 °C near the mouth of the Somass River (Port Alberni) 65 km inland. Water temperatures in the flow-regulated Stamp River, which contribute about 80-90% of summer flows to the lower Somass, typically averaged 18-20 °C during peak Sockeye migration (18.7 ± 1.3 °C, 95th percentile: 20.9 °C ibid). As the Stamp reaches lower elevations, solar warming and the influx of warmer waters from the smaller, shallower Sproat Lake system can add 0.5-1.0 °C to summer water temperatures in the lower Somass (18.9 ± 1.6 °C, 95th percentile: 21.6 °C; Hyatt et al. 2015).

Adult Sockeye bound for Great Central and Sproat Lakes generally commence upstream migration in June through September, with peak counts in mid-July, but upstream migration of either stock may be inhibited if Somass temperatures exceed 19-20 °C (Hyatt et al. 2015; Pellett et al. 2015). Sproat River temperatures, often exceeding the observed average of 21.3 ± 1.8 °C on average in July and August (and, on occasion, 22-25 °C: 95th percentile: 24.3 °C), pose an additional challenge for Sproat-bound Sockeye after ascending the Somass River (ibid).

A positive, long-term time-trend (0.17 °C per decade) was evident in the meteorological data for the summer months (July-September, 1918-2012; Mann-Kendall z-score = 5.5, $P < 0.01$, $n = 95$) and likely influences water temperatures as well (Hyatt et al. 2015).

Docee River

Docee River is a short stream (<1 km) that drains Long Lake, a clear, cold 21 km^2 waterbody in the Central Coast district of British Columbia (Figure 1, Figure 9; Table 1). The *oceanic*-type climate is characterized primarily by cool, wet summers and mild, wet winters strongly influenced by air masses flowing east from the Pacific Ocean (Figure 2, Figure 3).

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[7] Designated *Cfb* in the Köppen classification system (Peel et al. 2007). The *Cfb* climate is distinguished by several factors: mean annual air temperature ranges between 0 - 22 °C; and even the driest month of the year receives more than 30 mm of precipitation on average.

[8] Totalling 1,911 mm annually, including 114 cm of snow (ENVIRONMENT CANADA station 1036206 PORT ALBERNI A, 49°15'N x 124°50'N, elev. 2.4 m). Coastward, rainfalls may total 3,000-6,000 mm.

The watershed is located in the productive coniferous forests of the COASTAL WESTERN HEMLOCK biogeoclimatic zone (Figure 4). Average summer temperatures coastward of the lake range from 13-14 °C (Figure 5) with total annual precipitation of 2,564 mm, including 48 cm of snow.[9] As opposed to the Somass system, where river discharge is dominated by winter rain events, the Long Lake basin and Docee River hydrology is seasonally-driven by nival and glacial melt, as much of the drainage basin is further inland at higher elevations (Hyatt et al. 2005; Stiff et al. 2015b). This results in a highly variable seasonal hydrograph, as demonstrated at gauged streams elsewhere in the region (e.g. Wannock Creek, outlet for Owikeno Lake), with minimum flows generally occurring in late winter/early spring, peak freshet between May-July, followed by intermittent maximum flows due to autumnal rains (Figure 6).

Migrating adult Sockeye normally appear at Wyclees Lagoon by late June (Figure 9). Sockeye move up the Docee River in July and August and hold in Long Lake until spawning commences in lake tributaries beginning in September (Stiff et al. 2015b). Mean daily water temperature observations for the Docee River during the Sockeye migratory period were limited (2004-2008), averaging 15.2 ± 2.4 °C (95% of observations <19 °C). Temperature data were characterized by moderate inter-annual variation (11-17 °C), likely associated with ocean climate cycles (ibid)[10]. A weakly positive long-term time-trend (0.14 °C per decade) was evident in the meteorological data for the summer months (July-September, 1944-2012; Mann-Kendall z-score = 4.3, $P < 0.01$, $n = 69$; Stiff et al. 2015b).

Babine River

The Babine Sockeye index stock originates in the Nechako Plateau, in the central interior of British Columbia (Figure 1, Figure 2), which exhibits the sub-arctic continental climate (Figure 3) of the SUB-BOREAL SPRUCE biogeoclimatic zone (Figure 4). Located in the lee of the Skeena Mountain ranges, this interior watershed is drier than coastal regions. Its boreal climate is characterized by warm summers, cold winters, and relatively low but fairly uniformly distributed total annual precipitation[11].

Sockeye Salmon bound for the Babine watershed begin to arrive at the mouth of the Skeena River in June. Adult Sockeye take, an average of 3-5 weeks to migrate 260 km up the Skeena River and 96 km up the Babine River tributary, with peak arrival at the counting site at the outlet of Babine Lake (Figure 10) in mid-August (Stiff et al. 2015a).

Mean summer air temperatures in the upper Babine area tend to peak in July, typically at 14-15 °C, with maximums of 20-21 °C during Sockeye migration (Figure 5). A positive long-term time-trend (0.17 °C per decade) was evident in the meteorological data for the summer months (July-September, 1908-2014; Mann-Kendall z-score = 5.4, $P < 0.01$, $n = 107$; Stiff et al. 2015a). Total annual precipitation averages 538 mm, and occurs mostly over the winter months in the form of snow[12]. As mean air temperatures rise above zero in April, high elevation snowmelt results in maximum stream freshet, usually in mid-June, typical of nival- or mixed nivo-glacial watersheds (Figure 6). Field observations during peak migration (2003-2014) suggested daily mean water temperatures of ~15 ± 2 °C (Figure 7); 95% of observations were <19 °C (Stiff et al. 2015a). Mean annual Babine River discharge is 270 m^3/s (Table 1).

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[9] Climate normals (1971-2000) at EGG ISLAND meteorological lighthouse station 1062646 (51°15'N x 127°50'N, elev. 14 m) – snow to rain ratio may therefore not be representative of Long Lake watershed at higher elevation on mainland.

[10] i.e., EL NIÑO SOUTHERN OSCILLATION (ENSO) and PACIFIC DECADAL OSCILLATION (PDO) ocean climate cycles.

[11] Köppen climate classification: *Dfc*. Warm summers, cold winters, with mean temperatures below -10 °C for 2-3 months.

Meziadin River

The Meziadin is the primary Sockeye-producing watershed in the Nass River system (Bocking et al. 2002), which flows 380 km from high in the SPATSIZI PLATEAU (near the source of the Skeena River) to the Pacific Ocean north of Prince Rupert, British Columbia (Figure 1, Figure 2). Meziadin Lake is situated at 244 m above sea level on the lee side of the COAST MOUNTAINS where the headwater lake drains into the Nass via the 6-km Meziadin River (Table 1, Figure 11). The climate is cool and humid, with abundant annual precipitation, but relatively dry summers (Figure 3),[13] somewhat similar to coastal watersheds to the south. Cooler northern temperatures result in coniferous forests of the INTERIOR CEDAR-HEMLOCK biogeoclimatic zone (Figure 4).

The annual precipitation pattern is not unlike other central and north coast watersheds located somewhat further south, with most precipitation falling in the winter, 30-50% of it as snow (Figure 5)[14]. Meziadin River is ungauged, with only rough water level observations available from a salmon counting site at the Meziadin fishway (Stiff et al. 2015c), but the hydrology is likely seasonally-driven by nival and glacial melt, similar to the Docee/Long Lake system where much of the drainage basin is at higher elevations. The result is a highly variable seasonal hydrograph (damped by Meziadin Lake), with minimum flows occurring in late winter/early spring, peak melt-water freshet in May-July, followed by intermittent maximum flows due to autumnal rains, as demonstrated at Surprise Creek, a gauged stream draining into Meziadin Lake from Bear Glacier National Park (Figure 6).

Average July-August air temperatures, when adult Sockeye Salmon are arriving in greatest numbers, ranged from 14-15 °C at the meteorological station in Stewart, B.C.[15] A weakly positive long-term time-trend (0.14 °C per decade) was evident in the meteorological data for the summer months (July-September, 1908-2012; Mann-Kendall z-score = 4.4, $P < 0.01$, $n = 105$), likely driving water temperatures up as well (Stiff et al. 2015c). Mean daily water temperature observations during peak migration (1999-2012) were 14.1 ± 2.3 °C (Figure 7); 95% of observations were <18 °C (Stiff et al. 2015c).

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[12] ENVIRONMENT CANADA meteorological station 1078209 TOPLEY LANDING (Babine Lake) climate normals 1971-2010.

[13] Köppen climate type: *Dsc – dry summer sub-arctic.*

[14] ENVIRONMENT CANADA climate normals (1971-2010) for meteorological station 1067742 STEWART, approximately 50 km west of Meziadin, at the head of Portland Canal. Total annual precipitation of 1,842 mm (including 571 cm of snow).

[15] ENVIRONMENT CANADA climate normals (1971-2010) for meteorological station 1075384 NASS CAMP (located 90 km south of Meziadin at approximately the same longitude) records cooler and drier climate normals: Jul-Aug mean air temperatures of 15-16 °C, and total precipitation of 1,077 mm (including 300 cm of snow).

Tahltan River

Tahltan-bound adult Sockeye salmon enter freshwater near Wrangell, Alaska, to migrate upstream for about 240 km through the glacially-turbid Stikine River to return to their spawning grounds a further 55 km up the Tahltan River (Figure 1, Figure 12). The regional climatology is sub-arctic with relatively dry summers due to its northern location in the lee of the COAST MOUNTAIN range (Figure 2, Figure 3). Tahltan Lake, the largest lake in the Stikine drainage (Table 1), is situated in the BOREAL WHITE AND BLACK SPRUCE biome (Figure 4), approximately 100 km southwest of the town of Dease Lake, which receives about 425 mm of precipitation per year, about half of which falls as snow.[16] Summer air temperatures average 12-13 °C (Figure 5). Hydrologically, the Tahltan system reflects a mixed nivo-pluvial regime, with two maximums, the main one occurring after spring melt, and a more intermittent secondary rain-driven autumn maximum (Figure 6).

The highly-glaciated Stikine River basin remains relatively cold because of the dominant influence of glacial melt relative to smaller volume discharges from a few unglaciated tributaries and lakes (Hyatt et al. 2005). By contrast, the Tahltan Lake and River system are less glaciated, involve seasonal discharge of much smaller volumes of water, and consequently exhibit warmer thermal regimes than the Stikine mainstem. Observed mean daily water temperatures during peak migration (1985-2011) were 15.3 ± 1.7 °C (Figure 7); 95% of observations were <18 °C (Stiff et al. 2013). No long-term time-trend (Mann-Kendall z-score = 0.7, $P > 0.10$, $n = 67$) was evident for the summer months in the meteorological data (1945-2012; Stiff et al. 2013).

METHODS

This section describes the process used to translate downscaled global climate model (GCM) temperature data into daily water temperature estimates in natal watersheds associated with six Sockeye salmon index stocks (from south to north; Figure 1):

1. Somass watershed (Hyatt et al. 2015), specifically:
    a. the Somass portion of the Stamp/Somass river system; and
    b. the Sproat River tributary, on the west coast of Vancouver Island;
2. Docee River, in the Long Lake watershed in the Central Coast (Stiff et al. 2015b);
3. Babine River, the main Sockeye system tributary to the Skeena River in the North Coast (Stiff et al. 2015a);
4. Meziadin River, the main Sockeye system in the Nass watershed in the North Coast (Stiff et al. 2015c); and
5. Tahltan River, the principle Sockeye stock in the Stikine watershed in the BC-Alaska-transboundary region (Stiff et al. 2013).

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[16] Site of ENVIRONMENT CANADA'S regional DEASE LAKE meteorological station 1192340: 58°25'N x 130°00'W; 807 m above sea level)

GLOBAL CLIMATE MODELS

For each of the sites above, downscaled daily minimum and maximum air temperature time-series (January 1, 1950 – December 31, 2100) were obtained via the interactive map interface of the *Pacific Climate Impacts Consortium*[17] at the University of Victoria (PCIC 2014). These downscaled outputs are based on Global Climate Model (GCM) projections from the COUPLED MODEL INTER-COMPARISON PROJECT PHASE 5 (CMIP5[18] ; Taylor et al. 2012) and ANUSPLIN daily gridded climate data, from which the statistical and spatial properties of the downscaled scenarios are drawn (McKenney et al. 2011 and Hopkinson et al. 2011 in: PCIC 2014).

For the WESTERN NORTH AMERICA region[19], PCIC supplied an ensemble of twelve GCMs which account for projected climate changes spanning 90% or more of the full set of CMIP5 ensemble members (Cannon 2015). To obtain a wide diversity of future climate projections for this study, a subset of ten GCMs[20] was selected for downloading, including the top eight of the ordered GCMs, plus #10 and #11:

Order	1	2	3	4	5	6	7	8	9	10	11	12
Model	CNRM-CM5	CanESM2	ACCESS1-0	INMCM4	CSIRO-Mk3-6-0	CCSM4	MIROC5	MPI-ESM-LR	HadGEM2-CC	MRI-CGCM3	GFDL-ESM2G	HadGEM2-ES
Run	r1	r1	r1	r1	r1	r2	r3	r3	r1	r1	r1	r1
Calendar (days/year)	365/366	365	365/366	365	365	365	365	365/366	360	365/366	365	360
Used?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No

BIAS-CORRECTION METHODS

Climate model outputs may contain significant biases relative to regional or local conditions due to coarse resolution of the originating GCMs. PCIC (2014) provides output for each GCM source downscaled to a finer resolution using two bias-correction methods to reduce these effects:

1. The *Bias-Correction Spatial Disaggregation* method (BCSD) (Werner 2011; Maurer et al. 2008) includes modifications for incorporation of monthly minimum and maximum temperature instead of monthly mean temperature (Bürger et al. 2012). It also incorporates a bias-correction using detrended quantile mapping with delta method extrapolation (Bürger et al. 2013 in: PCIC 2014). BCSD begins with monthly data, disaggregated to a daily interval, which allows the GCM calendar to be mapped to a standard Gregorian calendar (i.e. 365 or 366 days per year, depending on leap years), such that future daily outputs match expected calendar dates.
2. The *Bias-Correction/Constructed Analogues with Quantile mapping reordering* (BCCAQ) method is a hybrid approach (Werner and Cannon 2015). It combines

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[17] PACIFIC CLIMATE IMPACTS CONSORTIUM, University of Victoria (Jan. 2014). Statistically-Downscaled Climate Scenarios. Downloaded from https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios from January-March 2017.

[18] CMIP5 courtesy of World Climate Research Programme's Working Group on Coupled Modelling.

[19] The WESTERN NORTH AMERICA (WNA) region is the "Giorgi region" that that encompasses British Columbia's coastal Sockeye stocks (Giorgi and Francisco 2000, in: PCIC 2014).

[20] Hadley GCMs were excluded from this study since Hadley outputs adhere to a fixed 360-day year, requiring further processing for direct comparison with other model outputs. When a GCM employs a 360-day calendar (with 30-day months), additional days must be created for January, March, May, July, August, October, and December (e.g. averaged from the previous and following days' temperatures), and removed for February. For example, see Dobor et al. 2015.

spatial information from a linear combination of historical analogues for daily large-scale fields from BCCA with quantile mapping (QMAP) of daily climate model outputs interpolated to a high-resolution grid (Maurer et al. 2010 and Gudmundsson et al. 2012 in: PCIC 2014). BCCAQ does not use monthly aggregates, and therefore can project changes in sub-monthly temporal variability. However, it is tied to the GCM calendar (365 days per year for all years for models used in this analysis) and date assignment in future leap years must be managed.

Although outputs are based on the same GCM data and therefore not fully independent, the two bias-correction methods (BCSD and BCCAQ) apply distinctly different processing approaches and can be reasonably assumed to provide equally plausible outcomes.[21] However, the BCCAQ method is more suitable for the type of vulnerability assessment indicator utilized in this study (described below), which is a form of warm-spell index that, to be meaningful, requires GCM-driven day-to-day variability in future temporal sequences. Whereas the BCSD method basically re-samples disaggregated monthly means of historical temperature observations, and is thereby bound by historical temporal properties, the BCCAQ method derives the daily temporal sequencing of events directly from the GCM, which allows for flexibility in the projection of future cold/warm/dry spell period lengths. Thus, analyses presented in the current report were restricted to outputs based on the BCCAQ method.

Gridded daily minimum and maximum temperature observations used as the target data for the BCCAQ downscaling were created using the Australian National University Spline (ANUSPLIN) implementation of trivariate, thin-plate, smoothing splines. ANUSPLIN interpolation of station observations was performed on a 1/12th degree grid (~10 km) for the period 1950–2010 by Hopkinson et al. (2011) and McKenney et al. (2011). Data extracted from ENVIRONMENT CANADA observing sites were quality controlled and corrected for station relocation and changes in the definition of the climate day. Corrected station data were interpolated onto the high-resolution grid using ANUSPLIN smoothing splines with elevation, longitude, and latitude as interpolation predictors.

REPRESENTATIVE CONCENTRATION PATHWAYS

For each GCM, two REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs) were selected.[22]

1. RCP 4.5 – This RCP represents a moderately optimistic low-emissions climate policy approach, comparable to the AR4 SRES B1 scenario, in which emissions peak around 2040, then decline.

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[21] Burger et al. (2013): "While the suite of GCMs and downscaling methods was slightly different, PCIC found that GCMs are the main source of projection uncertainty in BC, *so long as the downscaling methods are selected based on careful verification*, i.e., if methods that perform poorly under historical conditions are weeded out. [...] If the analysis was confined to downscaling methods that were established as reliable through independent verification [...] the influence of downscaling was strongly diminished, leaving GCMs as the main source of uncertainty."

[22] REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs) are greenhouse gas concentration trajectories (not emissions) adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5) in 2014 (superceding SPECIAL REPORT ON EMISSIONS SCENARIOS (SRES) projections published in 2000). The IPCC uses four new trajectories of atmospheric greenhouse gas concentration, known as Representative Concentration Pathways (RCP) for its Fifth Assessment Report. The four trajectories are denoted by the change to radiative forcings that would result from each concentration, e.g. RCP 4.5 would result in an increase of 4.5 Watts per square meter as compared to the preindustrial period (taken to be the year 1750). For more information on CMIP5 and the RCPs, see: van Vuuren et al., 2011: The Representative Concentration Pathways: An Overview. Climatic Change, 109 (1-2), 5-31

2. RCP 8.5 – For this RCP, emissions continue to rise throughout the 21st century, representing the pessimistic 'business-as-usual' AR4 SRES A2 trajectory.[23]

SITE-SPECIFIC DOWNSCALED DATA SELECTION

Grid-points for data selection were user-specified using a rectangular selection tool on the PCIC interactive map interface. A selection area encompassing a minimum of four grid-points was required to identify downscaled data for output. Given the heterogeneous topography of the study sites, the grid-points selected for data download were closely matched to the latitude-longitude location associated with the ENVIRONMENT CANADA climate stations used in previous retrospective analyses (e.g. Hyatt et al. 2015).

- The exception was for the Somass system: efforts to closely encompass the ROBERTSON CREEK meteorological station (near Great Central Lake, which is bounded by rugged Coastal Mountains) generated 1 of 4 data points in a significantly cooler location than the other 3 points.[24] The data selection rectangle was therefore relocated to the lower Somass area (Figure 8), corresponding to geographical coordinates (49.29167°N x 124.875°W) to (49.375°N x 124.958°W), to minimize bias in the downscaled data relative to local conditions.
- For the Docee River system (Figure 9), the data selection rectangle (50.625°N x 127.345°W) to (50.708°N x 127.458°W) encompassed the PORT HARDY meteorological reference station (Stiff et al. 2015b).
- For the Babine system (Figure 10), the data selection rectangle (54.79167°N x 126.208°W) to (54.875°N x 126.292°W) encompassed the TOPLEY LANDING meteorological station (Stiff et al. 2015a).
- For the Meziadin system (Figure 11), the data selection rectangle (55.875°N x 129.958°W) to (55.95833°N x 130.042°W) encompassed the STEWART meteorological station (Stiff et al. 2015c).
- For the Tahltan River system (Figure 12), the data selection rectangle (58.375°N x 129.958°W) to (58.458°N x 130.042°W) encompassed the DEASE LAKE meteorological reference station (Stiff et al. 2013).

DATA ANALYSIS

Air to Water Temperature

Minimum and maximum air temperature time-series for each model, method, and scenario were downloaded as NetCDF Version 3 files. The NetCDF files were converted via an MS-Excel (2007) spreadsheet using a NetCDF reader add-in[25], then saved in XLSX spreadsheet format. The spreadsheet data were imported and analyzed in SAS statistical analysis software (version 9.3). Downscaled minimum and maximum air temperature values were averaged across the four coordinates downloaded in each file. The resulting mean minimum and maximum temperature time-series were then merged by model, method, scenario, and date, to calculate daily mean temperature projections for each time-block. Daily mean air temperature estimates were organized into 30-year time-blocks associated with a reference period (1971-2000) and three 21st century time-periods (2011-2040, 2041-2070, and 2071-2100) for multiple GCMs.[26]

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[23] AR4 SRES A2 & B1 trajectory information: https://en.wikipedia.org/wiki/Special_Report_on_Emissions_Scenarios

[24] Gridded values may differ from climate stations and biases may be present at high elevations or in areas with low station density (Eum et al., 2014).

[25] NetCDF4Excel: NetCDF add-in for Excel 2.x (library version 3.6.3; build 2012.07.04)

A site-specific bias ranging from 0-3 °C remained for downscaled daily mean air temperature data on the 1/12th degree ANUSPLIN grid versus estimates derived from historical station observations for the reference period (1971-2000) for all study sites.[27] Thus it was necessary to obtain from PCIC the gridded historical ANUSPLIN temperature observations for the same geographical coordinates from which the modelled data were generated to adjust downscaled GCM data to local conditions. Linear regression was used to calibrate PCIC data for June-September against historical daily air temperatures for the baseline period (1971-2000) from the ENVIRONMENT CANADA meteorological stations associated with the Somass (ROBERTSON CREEK: Figure 8), Docee (PORT HARDY: Figure 9), Babine (TOPLEY LANDING: Figure 10), Meziadin (STEWART: Figure 11), and Tahltan (DEASE LAKE: Figure 12) watershed study sites. The site-specific regression coefficients were subsequently used to adjust the downscaled daily mean air temperature values for all time-periods.

Site-specific air-to-water temperature conversions utilized the logistic relationship for *daily mean water temperature* as a function of the *7-day centered moving average air temperature index* (7d-CMAT) as follows. Site 7d-CMAT indices were first calculated from the downscaled adjusted daily mean air temperatures, then converted to daily mean water temperature via nonlinear seasonal air-to-water temperature relationships derived for each study site (Somass and Sproat rivers: Hyatt et al. 2015; Docee River: Stiff et al. 2015b; Babine River: Stiff et al. 2015a; Meziadin River: Stiff et al. 2015c; Tahltan River: Stiff et al. 2013). Modelled air and water temperature statistics (mean, standard deviation, median, quartiles, minima, maxima) were calculated for each site, model, RCP scenario, and month across all years for each 30-year time-block. To reduce the influence of extremes, a range statistic based on the middle 50th percentile of model outputs (i.e., between the 25th percentile (P25) and the 75th percentile (P75)) was used in conjunction with mean and standard deviation to statistically-describe temperature projections for each stratum.

For Somass stocks, two watershed locations were assessed: the *lower Somass River* at the mouth of the Somass (a migratory 'decision-point' which must be navigated by both Great Central and Sproat Sockeye stocks), and the *Sproat River* tributary (which the Sproat Sockeye stock alone ascends), which flows into the Somass River 15 km above the Somass estuary. Though Sproat River is short (3 km), summer water temperatures tend to be 2-3 degrees warmer than the Somass River (Hyatt et al. 2015). Furthermore, tag analyses indicate that the decision to migrate for both Sockeye stocks is associated with lower Somass River temperature conditions (Pellett et al. 2015), thus Sproat-bound fish may be subject to a significant additional source of thermal stress and associated cumulative impacts. Therefore, projections for both Somass and Sproat water temperature time-series were assembled here, based on the same downscaled air temperature time-series for ALBERNI ROBERTSON CREEK, plus site-specific air-to-water temperature conversions.

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[26] PCIC provides statistically-downscaled daily Canada-wide climate scenarios at a gridded resolution of 300 arc-seconds (0.0833 degrees, or roughly 10 km) for the simulated period of 1950-2100. The variables available include minimum temperature, maximum temperature, and precipitation.

[27] Gridded daily mean temperature estimates from downscaled GCMs may differ from daily means obtained from regional climate stations due to spatial biases associated with topography and differences in elevation, especially in areas of low station density (Eum et al. 2014).

Salmonid vulnerability indices were then derived from the estimated daily mean water temperature time-series by Site, GCM, RCP, month and time-period, with a focus on the stock-specific months of adult Sockeye migration.

Exposure Indices

Daily mean air and water temperature time-series were used to calculate two Sockeye exposure indices for reference and future time-periods at each study site. The exposure indices are "peak-over-threshold" (POT) exceedance indicators, based on biologically-critical thresholds for two temperature variables: 20 °C threshold for daily mean air temperature; 19 °C for daily mean water temperature.

The 20 °C threshold for air temperature was selected based on the general finding that monthly mean air temperatures of 20 °C are considered an upper threshold for salmonid survival during adult life history stages (Mote et al. 2003). Essentially, cold-loving anadromous species are not generally found in systems where regional air temperatures average more than 20 °C per month (ibid). In addition, daily mean air temperature projections are directly available from GCM downscaling, and provide a trend indicator that is independent of site-specific air-to-water temperature conversion and associated errors.

The 19 °C threshold for water temperature was selected based on empirical evidence that adult Sockeye Salmon migration in freshwater is characterized by delays or stoppage when daily mean temperatures exceed this threshold (Hyatt et al. 2003; Hyatt et al. 2015). Temperatures in this range have been shown to be associated with decreased migration speed (Pellett et al. 2015), and continuous 'warm water' events, in which temperatures persistently exceed a critical threshold of 19 °C for 2-3 weeks or more, can lead to disease (Macdonald et al. 2000), high pre-spawn mortality (Cooke et al. 2004; Hinch and Martins 2011), and reduced reproductive success (Jensen et al. 2004).

Exposure Index #1 – Frequency of POT Events

The first index is a simple tally of the number of dates during the adult migration period (June-September) when daily mean temperatures peaked over the relevant threshold: 20 °C for air ($POT_{20\,°C}$); 19 °C for water ($POT_{19\,°C}$). Statistics (mean, median, quartiles, extremes) associated with the seasonal total frequency of POT dates were calculated for each model, month, and RCP scenario across all years for each 30-year time-block. The POT frequencies were further tabulated across all models and methods by time-block describing the median and range of POT events as the century progresses under the two RCP scenarios. Stacked bar charts were used to indicate the trend in the mean frequency of POT dates by month. Box-and-whisker plots were used to portray GCM variability in the trend analyses. Median, quartile, and range statistics associated with estimated daily mean air and water temperature across all years for each migratory month and time-period were plotted by model and RCP scenario to review trends over the 21st century.

Exposure Index #2 – Duration of POT Events

The second index is a measure of the duration of continuous dates when the thermal thresholds were exceeded during the adult migration period (June-September). This index provides information beyond a simple tally of exposure dates across the season, as the latter does not account for 'breaks' in the weather pattern and associated water temperature conditions that may be conducive to resumption of migration. The second exposure index was therefore based on the annual mean duration (in days) of *continuous* $POT_{20\,°C}$ air temperature and $POT_{19\,°C}$ water temperature events during the migratory period (June-September). The mean duration across all years within each time-block and month was tabulated for each GCM and RCP, and subsequently averaged across all models in bar charts and box plots to review the distribution (mean, median, and range) in future trends for each RCP emissions scenario.

RESULTS

SOMASS AND SPROAT RIVERS

Air and Water Temperature Projections

Synopsis: Trends in Somass monthly mean air temperature during the active migration period (June through September, with peak migration in July and early August; Hyatt et al. 2015) were projected to rise relatively consistently over the 21st century for all months, at varying rates according to GCM model and RCP scenario. Significant differences due to RCP began to manifest in the 2050s and were accentuated by the 2080s (Figure 13, top). Mean air temperature during peak migration is projected to rise 3 °C from the reference period under RCP 4.5 (i.e., from 18 to 21 °C) and 5 °C under RCP 8.5 (from 18 to 23 °C) (Table 2). Analogous water temperatures in the Somass are expected to rise 2-3 °C from baseline levels of 19-20 °C under both RCP trajectories. Sproat River water temperatures are also expected to rise 2-3 °C from reference levels of 20-22 °C over the next 90 years (Table 3).

Details: For the reference period (1971-2000), 50% of daily air temperature projections during the peak Sockeye migration months (July-August) fell between 16-20 °C, with median values of ~18 °C (Table 2). Median values for these months for both RCPs were projected to rise to ~19 °C by the 2020s, and ~20-21 °C by the 2050s. Divergence in projected air temperatures due to RCP trajectory was most evident by the 2080s, when median July-August air temperatures for the 'optimistic' RCP 4.5 scenario levelled out at 21 °C (with 75th percentile ≤ 23 °C; Figure 13, top left), whereas for the 'pessimistic' RCP 8.5 scenario, median air temperature projections rose to 23 °C (and 75th percentile ~25 °C; Figure 13, top right). By the end of the century, 50% of daily air temperature projections during the peak Sockeye migration months (July-August) fell between 19-23 °C under RCP 4.5, and 21-25 °C under RCP 8.5 (Table 2). This signifies a 3-5 °C increase in mean air temperatures during peak Sockeye migration months, depending on RCP trajectory.

The rise in projected air temperatures translated into small but significant (to salmon) increases in water temperature in the lower Somass (Figure 13, middle), as a function of the site-specific air-to-water temperature logistic model (Hyatt et al. 2015). Water temperatures were projected to increase from a monthly median of 19-20 °C during July-August peak migration in the reference period, to 21-22 °C by the 2080s. Both RCPs projected mean monthly water temperatures to exceed 20 °C by the 2020s in July and August, and 21 °C by the 2050s (Table 2). By the 2080s, monthly median temperatures exceeding 20 °C were projected to expand into June and September as well (Figure 13, middle).

Sproat River water temperatures, already ranging from 19-22 °C for July-August during the reference period, were projected to exceed 20 °C on average for the mid-summer months in the 2020s and extend to June and September by the 2050s (Table 3). By the end of the century, July-August temperatures may average 22-24 °C, with little difference attributable to RCP trajectory (Figure 13, bottom).

Exposure Indicator #1 – Frequency of POT Events

Rising regional air temperatures resulted in an increase in the 20-degree *peak-over-threshold annual frequency indicator* for daily mean air temperature over future time-periods. While the mean seasonal frequency of $POT_{20\,°C}$ dates (i.e., dates where air temperatures peaked-over-threshold of 20 °C) during the baseline period (1971-2000) was ~22 days[28] per year (of a total 122 days in the four-month season), by the 2050s (2041-2070), the mean frequency had more than doubled, with increases in all months (Figure 14, top left). For the 'optimistic' RCP 4.5 scenario, in which temperature increases abated to some degree by the 2080s (2071-2100), $POT_{20\,°C}$ events averaged 52 days out of a possible 122 season total (Table 4, left). In the more 'pessimistic' RCP 8.5 scenario, average air temperature by the 2080s was above 20 °C for 77 days (63%) of the June-September period.

The box-and-whisker plots add GCM variability to the air temperature POT projections (Figure 14, top right). In the 2050s, for example, the median total $POT_{20\,°C}$ frequency for RCP 4.5 was about 44 days for the June-September season, while the middle 50% of projections, representing the 25th to 75th percentile of time-period estimates (delineated by the box) fell between 39-51 dates, and the full range (defined by the whiskers) was from a minimum of 31 dates to a maximum of 61 dates (Table 4). Under the RCP 8.5 emissions trajectory, total seasonal $POT_{20\,°C}$ projections ranged from 37-74 dates for the 2050s, with a median of 53 dates, and 50% of estimates falling between 46-62 dates per year (Table 4). By the 2080s, the median $POT_{20\,°C}$ frequency ranged from 50 dates for RCP 4.5 to 75 dates for RCP 8.5, with equally plausible projections ranging from a minimum of 59 dates to a maximum of 100 dates (Table 4; Figure 14, top). This would suggest air temperatures averaging more than 20 °C for a minimum of 32% of the June-September season, to a maximum of 82% of the season by the end of the century, depending on RCP trajectory.

Monthly summaries indicated that during Somass Sockeye peak migration (July and August) mean air temperatures may push the frequency of $POT_{20\,°C}$ dates to >50% of each month (16-17 days) by the 2050s under the optimistic RCP 4.5 scenarios, but 19-20 days under the pessimistic RCP 8.5 scenario (Table 4, right). By the 2080s, average $POT_{20\,°C}$ dates in July and August may range from 18 to 26 days depending on RCP trajectory – i.e., occur 58-80% of the month.[29]

When air temperatures were converted to water temperatures in the lower Somass River, the POT frequency index indicated a near-doubling of dates where water temperatures exceeded 19 °C ($POT_{19\,°C}$) by the 2050s (Figure 14, middle). The average annual frequency increased from ~47 days in the reference period 1971-2000[30], to 66-72 days by the 2020s, and 78-90 days by the 2050s, depending on RCP scenario (Table 5). Marked differences in water temperature $POT_{19\,°C}$ dispersion statistics due to RCP scenario began to manifest in the 2050s, where the median ranged from ~78 days for RCP 4.5 (with 50% of projections between 75-87 days) to ~90 days for RCP 8.5 (80-96 days) (Table 5; Figure 14, middle). Put another way, 50 percent of all models and scenario outcomes indicated a range of 75-96 days presenting a thermal barrier to upstream Sockeye migration by the 2050s, representing 62-79% of the 122-day migratory period between June to September. Under RCP 8.5, at least one GCM projection indicated 105 days of potential thermal barrier dates by the 2080s, representing 86% of the season.

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[28] Roughly equivalent to the regional conditions in the observed data from ROBERTSON CREEK summarized in Figure 63, Hyatt et al. (2015), after adjusting for inclusion of the month of June in this analysis.

[29] Recall that where mean monthly air temperature exceeds 20 °C, salmon populations tend not to persist (Mote et al. 2003).

A breakdown by month indicated that, by the 2050s, mean monthly frequencies would be approaching the monthly maximum for July (25-27 days) and August (29-30 days) depending on RCP scenario (Figure 15; Table 5, right). By the 2080s, monthly frequencies might average 27-30 days for July and 30-31 days for August, depending on RCP. RCP trajectory appears to be a determinant factor for Somass River water temperature conditions by the end of the century for the months of June and September, determining whether the frequency of thermal barrier dates remain near 50% of the month for June and September (RCP 4.5) or range from 50-70% of June and 70-90% of September (Figure 15; Table 5, right).

Conditions in the warmer Sproat River tributary during the baseline period appeared to be already thermally stressful to migrants for most of the migration season, with water temperatures exceeding 19 °C for 84 days[31] on average (Table 6; Figure 14, bottom), leaving little temporal 'wiggle room' remaining in July ($POT_{19\,°C}$ = 24 days) or August ($POT_{19\,°C}$ = 30 days) (Figure 16). Most of the remaining increase in $POT_{19\,°C}$ events during future time-periods could only occur in June and September, as July and August approach maximum frequencies (Table 6, right). While the middle 50% range of model outputs projected seasonal total Sproat $POT_{19\,°C}$ frequencies of 105-113 days by the 2050s and 114-120 days by the 2080s under RCP 8.5, the more optimistic RCP 4.5 trajectory offered little respite during those future time-periods: 101-110 dates in the 2050s and 104-114 dates in the 2080s (Table 6). At least one RCP 8.5 model estimated a maximum of 121 days (99%) of the migratory period by the 2080s (Figure 14, bottom right).

Exposure Indicator #2 – Duration of POT Events

Air temperature, being highly variable on a day-to-day basis, averaged less than 3 days of continuous $POT_{20\,°C}$ events during the 1971-2000 baseline period, with a slight increase in the 2020s and 2050s (Figure 17, top left; Table 7). The effects of RCP trajectory on the duration start to manifest by the 2050s, and, by the 2080s, $POT_{20\,°C}$ event duration might average ~9 days under RCP 8.5, compared to ~5 days under RCP 4.5 (Figure 17, top right).

Daily water temperatures are generally more stable than daily air temperatures and therefore water temperature conditions, including stressful thermal conditions, may be more persistent. This was reflected in Somass River (Figure 17, middle), where the mean and median duration of $POT_{19\,°C}$ events were ~13 days during 1971-2000, but were projected to reach 19-20 days in length on average in the 2020s (50% of models: 16-22 days) under both RCP trajectories (Table 8). Differences in duration of about 5 days due to RCP showed up in the 2050s (median 27-32 days). This indicator leveled off through the 2080s, reaching 29 days under the RCP 4.5 emissions scenario (i.e., a potential thermal delay of four weeks), but under the 'business-as-usual' RCP 8.5 scenario, median $POT_{19\,°C}$ event duration jumped to 56 days (eight weeks), or 39-63 days for the middle 50% of projections (Table 8). Minimum delays were projected to be 20 days – or three weeks – by the end of the century (RCP 4.5), and 36 days (five weeks) under RCP 8.5 (Table 8).

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[30] The Somass water temperature indicator was comparable to, but slightly higher, than Figure 65: Stamp River (Hyatt et al. 2015), since the Somass is 0.5-1.0 °C warmer than the Stamp. This chart also includes the month of June.

[31] The $POT_{19\,°C}$ frequency index above exceeded the $POT_{20\,°C}$ index illustrated in Figure 67: Sproat River (Hyatt et al. 2015) for two reasons: different (lower) thermal threshold employed here; and this study also includes the month of June.

In Sproat River, mean duration was already close to four weeks (27 days) during the reference period 1971-2000, reaching 40 days by the 2020s (Figure 17, bottom left), with 50% of all projections between 35-45 days by that time-period (Table 9; Figure 17, bottom right). This indicator began to level off to some degree for RCP 4.5 in the 2050s (46-54 days duration) and 2080s (48-66 days), but rose to 71-100 days for the 2080s for RCP 8.5 (Table 9). At least one RCP 8.5 projection indicated an *average* of 110 days of $POT_{19\,°C}$ conditions in the Sproat River for the 2071-2100 period (Figure 17, bottom right; Table 9).

DOCEE RIVER

Air and Water Temperature Projections

Synopsis: Regional mean air temperatures were projected to rise steadily over the 21st century, depending on GCM model and RCP scenario (Figure 18) for all months of the active migration period for Long Lake-bound Sockeye (July to mid-August, with peak migration in July; Stiff et al. 2015b). Mean air temperature during peak migration in July was projected to rise ~3 °C from the reference period under RCP 4.5 (i.e., from ~14 °C), and ~4 °C under RCP 8.5 (to ~18 °C) (Table 10). Analogous water temperatures in Docee River are expected to rise 3-4 °C from baseline levels, from 13 to 16 °C under RCP 4.5 and 13 to 17 °C under RCP 8.5 trajectories.

Details: For the reference period (1971-2000), the middle 50th percentile of daily air temperature projections during peak Sockeye migration in July fell between 13-15 °C at Port Hardy (~80 km southwest of the Docee watershed), with median values of 14 °C (Table 10). Median temperatures for July for both RCPs were projected to rise to 15 °C by the 2020s, and 16 °C by the 2050s. Significant divergence in projected air temperatures between RCP trajectories was indicated for the 2080s, when median July air temperatures for the 'optimistic' RCP 4.5 scenario remained at 16 °C (with 50% of projected estimates between 15-17 °C) while July median air temperatures were project to increase to 18 °C (with 50% of projections between 16-19 °C) for the 'pessimistic' RCP 8.5 scenario (Figure 18, top). This signifies a 3-4 °C increase in mean air temperatures during peak Sockeye migration, depending on RCP trajectory.

The projected rise in regional air temperatures translated into increases of 3-4 °C in water temperature in Docee River over the century (Table 10), as a function of the site-specific air-to-water temperature logistic model (Stiff et al. 2015b). Docee water temperatures were projected to increase from a monthly median of 13 °C during July peak migration in the reference period by 1 °C for each future time-block under the RCP 4.5 trajectory, but accelerate under RCP 8.5 by another degree by the 2050s (Figure 18, bottom). By the end of the century, the 75th percentile of all model projections was 17 °C and 18 °C for RCP 4.5 and RCP 8.5, respectively (Table 10).

Exposure Indicator #1 – Frequency of POT Events

Historical projections indicated an average of less than one day per year where mean air temperature exceeded 20 °C during the baseline period 1971-2000 (Table 11, Figure 19, top left)[32]. While the mean frequency of $\mathrm{POT}_{20\,^{\circ}\mathrm{C}}$ events for air temperature increased over future time-periods, the total frequency during peak migration in July was projected to average only 1-3 days per season, depending on RCP trajectory, by the 2050s. Significant divergence due to RCP occurred by the 2080s, however, when the mean $\mathrm{POT}_{20\,^{\circ}\mathrm{C}}$ event frequencies were 2 and 12 days per season for RCP 4.5 and RCP 8.5, respectively. Median (P50) and P75 values are likely more useful indicators than the mean, given the occasional extreme model outputs: the medians were 1.3 and 7.8 dates in the 2080s, and 75% of projections (P75) were less than 1.9 and 10.4 dates for low and high RCPs, respectively (Figure 19, top right; Table 11).

The corresponding number of dates where water temperature exceeded 19 °C ($\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events)[33] was basically negligible through the 2020s and 2050s even for the 'pessimistic' RCP 8.5 scenario, for which the mean/median frequency averaged < 2 $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events per season (Table 12 and Figure 19, bottom). While at least one model projected a seasonal total of almost 60 $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events under RCP 8.5 in the 2080s, the median annual total was ~7 events (over four months), and 75% of the models projected no more than 11 events per year (Table 12). September appeared to accrue the largest increases in $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events, followed by August (Figure 19, bottom left; Figure 20), which fall later than peak Sockeye migration into the Long Lake system.

Exposure Indicator #2 – Duration of POT Events

The duration of regional $\mathrm{POT}_{20\,^{\circ}\mathrm{C}}$ air temperature events lasted on average only one day in the reference period 1971-2000[34], and showed only a minimal increase over future time-periods, hovering around a mean of ~2-3 days, even under the RCP 8.5 scenario in the 2080s (Figure 21, top; Table 13).

The $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ water temperature duration indicator[35] indicated potential delays due thermal barriers lasting, on average, less than 3-4 days regardless of RCP trajectory through to the 2050s (Figure 21, bottom). By the end of the century, under RCP 8.5, the duration of $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events in Docee River could exceed 8 days on average, but that mean is influenced by a single model projecting more than 20 days, thus the median duration of 6 days, with a P75 of 8 days, may be a more reasonable estimate (Table 13; Figure 21, bottom).

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[32] Roughly analogous to the frequency of POT20 dates in the observed data from PORT HARDY, illustrated in Figure 58 of Stiff et al 2015b, after adjustment for differing air temperature thresholds employed.

[33] Results for the POT19 analysis above naturally appear lower than the POT18 analysis depicted in Figure 60 of Stiff et al (2015b).

[34] Similar to the 1970s – 2000s decades depicted in Figure 59 of Stiff et al (2015b) after adjusting for differences in air temperature threshold used.

[35] Due to a difference in the water temperature threshold employed, the POT19 duration indicator here appears lower than that of the POT17 analysis depicted in Figure 59 of Stiff et al (2015b).

BABINE RIVER

Air and Water Temperature Projections

Synopsis: Trends in Babine monthly mean air temperature during the active migration period (mid-July to mid-September, with peak migration in mid-August; Stiff et al. 2015a) were projected to rise over the 21st century for all months, at varying rates according to GCM model and RCP scenario (Figure 22). Mean air temperature during peak migration in August was projected to rise 2 °C from the reference period under RCP 4.5 (i.e., from 14-16 °C), but up to 5 °C under RCP 8.5 (from 14-19 °C) (Table 14). Analogous water temperatures in Babine River are expected to rise 2-3 °C from baseline levels, from 15-17 °C under RCP 4.5 and 15-18 °C under RCP 8.5 trajectories.

Details: For the reference period (1971-2000), 50% of daily air temperature projections during peak Sockeye migration in August fell between 11-16 °C, with median values of 14 °C (Table 14). Median values for these months for both RCPs were projected to rise to 15 °C by the 2020s, and 16 °C by the 2050s. Significant divergence in projected air temperatures between RCP trajectories was indicated for the 2080s, when median August air temperatures for the 'optimistic' RCP 4.5 scenario stabilized at 16 °C (with the middle 50% of projected estimates between 14-19 °C; Figure 22, left), while August median air temperature projections rose to 19 °C (with P25-P75 projections between 16-22 °C) for the 'pessimistic' RCP 8.5 scenario (Figure 22, right). This signifies a 2-5 °C increase in mean air temperatures during peak Sockeye migration, depending on RCP trajectory.

The projected rise in regional air temperatures translated into increases of 2-3 °C in water temperature in Babine River over the century (Table 14), as a function of the site-specific air-to-water temperature logistic model (Stiff et al. 2015a). Babine water temperatures were projected to increase from a monthly median in the reference period of 15 °C (P25-P75 of 14-16 °C) during August peak migration by 1 °C in each of the 2020s and 2050s future time-blocks for both RCP trajectories, and a further 1 °C for the RCP 8.5 trajectory by the 2080s (Figure 22). However, the 75th percentile of all model projections in the 2080s was <=18 °C for RCP 4.5 and <=19 °C for RCP 8.5 (Table 14).

Exposure Indicator #1 – Frequency of POT Events

Cool air temperatures in this northern watershed were reflected in an average of less than three $\mathrm{POT}_{20\,^{\circ}\mathrm{C}}$ events per year during the baseline period 1971-2000 (Table 15, top left; Figure 23, top)[36]. While the mean frequency over future time-periods doubled historic values by the 2020s, and tripled them by the 2050s, the total frequency of $\mathrm{POT}_{20\,^{\circ}\mathrm{C}}$ dates during August averaged only 4-6 days during the 2050s, and 5-12 days in the 2080s, for RCP 4.5 and RCP 8.5, respectively (Table 15, top right).

The resulting effects on $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ events for Babine water temperature were minor (Table 16, Figure 23). $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ occurrences[37] were negligible through the 2020s and 2050s even for the 'worst-case scenario', RCP 8.5, for which the mean/median frequency was 2-3 $\mathrm{POT}_{19\,^{\circ}\mathrm{C}}$ dates for the season (Figure 23, bottom left). While at least one GCM model projected a seasonal total of 24 $POT_{19\,°C}$ annual events under RCP 8.5 in the 2080s (Figure 23, bottom right), the average annual total was 9 days (over four months), and 75% of the models projected no more than 13 days per year (Table 16, left). Though $POT_{20\,°C}$ dates for air temperature were distributed primarily in July and August, $POT_{19\,°C}$ dates for water temperature occurred primarily in August (P75 < 11 days for RCP 8.5), with minor incursions into September (P75 < 3 days) by the end of the century (Figure 23, bottom left; Figure 24).

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[36] Roughly analogous to the frequency of POT20 dates in the observed data from TOPLEY LANDING, illustrated in Figure 38 of Stiff et al 2015a.

[37] Results for the POT19 analysis above naturally appear lower than the POT18 analysis depicted in Figure 40 of Stiff et al (2015a).

Exposure Indicator #2 – Duration of POT Events

The duration of $POT_{20\,°C}$ air temperature events in the Babine watershed showed a minimal increase over future time-periods, from a mean of ~2 days during the baseline period[38], to a 'worst-case scenario' of 4.5 ± 1.7 days in the 2080s (Figure 25, top; Table 17, left).

The $POT_{19\,°C}$ water temperature indicator[39] indicated potential delays due thermal barriers lasting, on average, less than 4-6 days regardless of RCP trajectory through to the 2050s (Figure 25, bottom). By the end of the century, under RCP 8.5, the duration of $POT_{19\,°C}$ events in Babine River could exceed 7 days on average, with a P75 of 9 days (Figure 25). For that RCP, at least one model indicated an average length of 14 days (Table 17, right), which could potentially impact Sockeye migrants negatively, since most of these events would occur in August and early September (Figure 24).

MEZIADIN RIVER

Air and Water Temperature Projections

Synopsis: Trends in Meziadin monthly mean air temperature during the active migration period (July to mid-September, with peak migration from July to mid-August; Stiff et al. 2015c) were projected to rise by about 1 °C every 30 years during the 21st century, at slightly varying rates according to GCM model and RCP scenario (Figure 26). By the end of the 21st century, mean air temperature during peak migration in July and August was projected to rise 3 °C from the reference period under RCP 4.5 (i.e., from 14 to 17 °C), and up to 4-5 °C under RCP 8.5 (from 14 to 18-19 °C) (Table 18). Water temperatures in Meziadin River were expected to rise 2-3 °C from baseline levels over the century, from 15 °C to 17 °C under RCP 4.5, and from 15 °C to 17-18 °C under RCP 8.5 trajectories.

Details: For the reference period (1971-2000), the middle 50% of daily air temperature projections (P25-P75) during peak Sockeye migration in July-August fell between 13-16 °C, with median values of 14-15 °C (Table 18). Median values for these months for both RCPs were projected to rise by slightly less than 1 °C every 30 years for RCP 4.5 and slightly more than 1 °C per time period for the RCP 8.5 trajectory. By the 2080s, median July-August air temperatures reached a maximum for the RCP 4.5 scenario at 17 °C (with middle 50% of projected estimates between 15-18 °C), and at 18-19 °C (with 50% of projections between 17-21 °C) for the RCP 8.5 scenario (Table 18; Figure 26). This suggests a potential 3-5 °C increase in mean air temperatures during peak Sockeye migration, depending on RCP trajectory, by the year 2100.

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[38] Similar to the 1970s – 2000s decades depicted in Figure 39 of Stiff et al (2015a).

[39] As for the frequency indicator, the POT19 duration indicator analysis here naturally appears lower than the POT18 analysis depicted in Figure 41 of Stiff et al (2015a).

Rising regional air temperatures translated into increases of 2-3 °C in water temperature in Meziadin River over the century (Table 18), as a function of the site-specific air-to-water temperature logistic model (Stiff et al. 2015c). Resulting August water temperatures were generally higher by ~1 °C relative to July water temperatures (unlike air temperatures, for which July estimates were slightly warmer than for August) (Figure 26). Meziadin water temperatures during peak migration were estimated to also increase by ~1 °C in the 2020s and 2050s future time-blocks for both RCP trajectories. A visible effect due to RCP fully emerged in the 2080s, for which an additional 1 °C increase occurred for RCP 8.5 but not the RCP 4.5 trajectory. However, the 75th percentile of all model projections in the 2080s was, for RCP 4.5, <=17 °C in July and <=18 °C in August, and for RCP 8.5, <=18 °C and <=19 °C, respectively (Table 18). Overall it appears that Meziadin water temperatures during Sockeye migration may increase 2-3 °C relative to the reference period over the course of the century, from a P25-P75 percentile initial range of 14-17 °C, up to 16-19 °C.

Exposure Indicator #1 – Frequency of POT Events

During the baseline period (1971-2000), the Meziadin watershed typically averaged ~1 $POT_{20\,°C}$ air temperature event per year (Figure 27, top)[40]. The seasonal mean frequency of dates for which mean air temperatures exceeded 20 °C was projected to rise to 5 days by the 2020s. A divergence in the expected frequencies due to RCP begins to manifest in the 2050s through to the 2080s. Most of the increases occurred during peak migration in July and August (Figure 27, top left; Table 19, right).

When translated into water temperatures (Stiff et al. 2015c), $POT_{19\,°C}$ occurrences are expected to be infrequent through the 2020s and 2050s, with annual mean and median frequencies of less than two $POT_{19\,°C}$ events[41], primarily in August (Figure 27, bottom; Figure 28). While at least one model projected an annual mean of 23 $POT_{19\,°C}$ events by the 2080s under RCP 8.5, 75% of projections indicated no more than 8-9 $POT_{19\,°C}$ events per year in Meziadin River (Figure 27, bottom; Table 20).

Exposure Indicator #2 – Duration of POT Events

The duration of regional air temperature $POT_{20\,°C}$ events as measured at STEWART likewise showed a minimal increase over future time-periods, from a mean of ~2 days during the baseline period[42], to a 'worst-case scenario' of ~4 ± 1.2 days in the 2080s (Figure 29, top; Table 21, left).

The Meziadin River $POT_{19\,°C}$ event duration indicator[43] for water temperature indicated minor increases in the length of potential delays due to thermal barriers in the 2020s and 2050s of 3-5 days, depending on RCP scenario (Figure 29, bottom; Table 21, right). By the end of the century, the mean and median estimates of $POT_{19\,°C}$ duration would be expected to be 5-8 days, with some RCP 8.5 models projecting as high as two weeks.

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[40] Roughly analogous to the frequency of $POT_{20\,°C}$ dates for air temperature in the observed data since 1970 from STEWART (Figure 43 in Stiff et al 2015c).

[41] Equivalent to the last four decades in Figure 45 of Stiff et al (2015c).

[42] Similar to the 1970s-2000s decades depicted in Figure 44 of Stiff et al (2015c).

[43] As for the frequency indicator, the $POT_{19\,°C}$ duration indicator analysis here correctly appears lower than the $POT_{18\,°C}$ analysis depicted in Figure 46 of Stiff et al (2015c).

TAHLTAN RIVER

Air and Water Temperature Projections

Synopsis: Trends in Tahltan monthly mean air temperature during the active migration period (mid-July to early-September, with peak migration between mid-July and mid-August; Stiff et al. 2013) were projected to rise 2-3 °C during the 21st century for all months for RCP 4.5 scenarios and 4-5 °C for RCP 8.5 scenarios (Figure 30, top). Mean air temperature during peak migration over July-August was projected to rise ~2 °C from the reference period under RCP 4.5 (i.e., from 12-13 °C to 14-15 °C), but up to 5 °C under RCP 8.5 (from 12-13 °C to 17 °C) (Table 22). Corresponding July-August water temperatures in Tahltan River are expected to rise under RCP 4.5 scenarios 1-2 °C from baseline levels of 14-15 °C up to 16-17 °C, or, under RCP 8.5 trajectories, 3-4 °C to a mean of 17-18 °C by 2100.

Details: For the reference period (1971-2000), mean and median air temperatures ranged from ~12-13 °C in July and August, with 75% of projections below 14-15 °C (Figure 30, Table 22). July air temperatures tended to be ~1 °C warmer than August. Median values for these months for both RCPs were projected to rise 1 °C per time period through to the 2050s, but the rate of increase slows for RCP 4.5 to a median of 14-15 °C by the end of the century, whereas median air temperatures for RCP 8.5 scenarios may rise to 17 °C. Under this scenario the P75 for air temperature projections during July in the 2080s reached 20 °C. Depending on RCP trajectory, these data signify a 2-4 °C increase in mean air temperatures during peak Sockeye migration through the 21st century (Figure 30, top).

The projected rise in regional air temperatures corresponds to increases of 2-4 °C in water temperature in Tahltan River over the century (Figure 30, bottom), as a function of the site-specific air-to-water temperature logistic model (Stiff et al. 2013). Tahltan water temperatures were projected to increase from a monthly median in the reference period of 14-15 °C during peak July-August migration by 1 °C in the 2020s and 2050s future time-blocks for both RCP trajectories, and a further 1 °C for the RCP 8.5 trajectory by the 2080s (Table 22). As a result of the logistic transformation, water temperatures in August were slightly warmer (~1 °C) than in July until they converged later in the century (Figure 30, bottom). The 75th percentile of all model projections in the 2080s was <=18 °C and <=19 °C for RCP 4.5 and RCP 8.5, respectively. Maximum water temperatures exceeded 20-21 °C only infrequently (Figure 30, bottom).

Exposure Indicator #1 – Frequency of POT Events

Historically cool air temperatures in this northern watershed were reflected in an average of less than one $POT_{20\,°C}$ event per year during the baseline period 1971-2000 (Table 23, Figure 31, top)[44]. While the mean frequency increased over future time-periods, the total frequency of $POT_{20\,°C}$ dates during July and August averaged only 4 (RCP 4.5) to 7 (RCP 8.5) days during the 2050s. Significant divergence due to RCP occurred by the 2080s, however, where the mean frequencies ranged from 6-19 days per season for RCP 4.5 and RCP 8.5, respectively (Table 23).

The resulting effects on the frequency of $POT_{19\,°C}$ events for Tahltan water temperature were minor (Table 24). $POT_{19\,^{\circ}C}$ occurrences[45] were negligible through the 2020s and 2050s even for the 'worst-case scenario', RCP 8.5, for which the mean/median frequency was 5-6 $POT_{19\,^{\circ}C}$ events for the season (Figure 31, bottom). While at least one model projected a seasonal total of 50 $POT_{19\,^{\circ}C}$ annual events under RCP 8.5 in the 2080s, the average annual total was 16-17 occurrences (over four months), and 75% of the models projected no more than 22 dates per year (Table 24, left). Future increases in $POT_{19\,^{\circ}C}$ events occurred primarily in July and August, followed by June (Figure 31, Figure 32; Table 24, right).

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[44] The analogous POT20 dates frequency plot in the observed data from TOPLEY LANDING, illustrated in Figure 58 of Stiff et al 2013 was based on a thermal threshold of 17°C and is therefore characterized by more events.

Exposure Indicator #2 – Duration of POT Events

The duration of $POT_{20\,^{\circ}C}$ air temperature events in the Tahltan watershed showed a minimal increase over future time-periods, from a mean of ~2 days during the baseline period[46], to a 'worst-case scenario' of 3.4 ± 0.9 days in the 2080s (Figure 33, top; Table 25).

The $POT_{19\,^{\circ}C}$ water temperature duration indicator[47] indicated potential delays due thermal barriers lasting 5-7 days on average, regardless of RCP trajectory through to the 2050s (Figure 33, bottom left). By the end of the century, under RCP 8.5, the duration of $POT_{19\,^{\circ}C}$ events in Tahltan River could last 8-9 days on average, with a P75 <=10 days (Figure 33, bottom right). For that RCP, at least one model indicated an average length of more than two weeks (16 days), which could potentially impact Sockeye migrants negatively, since most of these events would occur in July and August (Figure 32).

DISCUSSION

Air and water temperatures are on the rise in the watersheds of British Columbia. Over the past 60 years (1950-2010), seasonal mean air temperatures have increased at most B.C. stations by at least 0.5-2.5 °C, with greatest increases in winter and spring, and, at southern and coastal stations in the summer months (Bush et al. 2014, p. 28). Climate model projections indicate that further increases of 1.5-4.0 °C (low-high emissions scenarios) should be anticipated for summer and fall seasons in British Columbia by the middle of the 21st century (Bush et al. 2014, p. 34). Freshwater thermal and hydrological regimes will change in response.

The potential impacts of regional warming on wild salmon via disruption to marine, terrestrial and freshwater ecologies are increasingly well-documented (Hinch and Martins 2011; Martins et al. 2012). Though Sockeye and other salmonids are widely distributed along Canada's Pacific coast, and therefore highly adapted to diverse environments, individual stocks' life history strategies, from the timing of egg-incubation to adult return-migration, are often fine-tuned to local watershed conditions, and therefore sensitive to climate variation and change (CVC) effects on multiple life cycle events (McDaniels et al. 2010). While some climate-induced environmental changes may yield positive outcomes for certain life stages of certain stocks (e.g. juvenile growth in sub-optimally cool locations or northern locales;

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[45] Results for this POT19 analysis naturally appear lower than the POT17 analysis depicted in Figure 59 of Stiff et al (2013).

[46] Similar to the 1970s – 2000s decades depicted in Figure 59 of Stiff et al (2013).

[47] As for the frequency indicator, the POT19 duration indicator analysis here naturally appears lower than the POT18 analysis depicted in Figure 61 of Stiff et al (2013).

Beer and Anderson 2013; Mauger et al. 2016; Bryant et al. 2009), there is a general concern that the cumulative impacts of CVC across generations will most likely negatively affect population production and survival (Healey and Bradford 2011; Campbell et al. 2014). Sustaining wild salmon genetic diversity will therefore require an accelerated understanding of the vulnerability of specific salmonid life stages to the variable impacts of CVC in the heterogeneous regional geography of British Columbia (Walker and Sydneysmith 2008; Burrows et al. 2011).

To achieve this, fisheries resource managers need to develop models that reduce uncertainties associated with: (a) projections of regional climate changes; and (b) our limited comprehension of the physical controls on biological systems (Schindler et al. 2008). Regarding the latter, this analysis draws on life-history event and process models from "data-rich" salmon populations and river systems (e.g. Hyatt et al. 2003; 2015; Stiff et al. 2015a;b;c), distributed across five major drainages and four biogeoclimatic zones, to define stream temperature controls in the freshwater migration corridors for adult Sockeye migrants. To reduce uncertainty in regional climate projections, climate change scenarios and downscaling methods were selected based on the objectives of this analysis (Murdock and Spittlehouse 2011), which required time-series at a daily interval for derivation of temperature exposure indicators for risk assessment.

GCM PROJECTIONS

Air temperature outputs from ten "state-of-the-art" CMIP5[48] GCMs, tailored to the WESTERN NORTH AMERICA region[49], were downscaled to site-specific meteorological stations from which adjusted and homogenized climate data[50] were previously used to generate statistical air-to-water temperature relations (e.g. Hyatt et al. 2015).

Some assumptions were made with respect to selection of REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs) for GCM model outputs adopted by the IPCC for its fifth Assessment Report (IPCC 2014). RCPs describe four potential climate trajectories, depending on the concentration of greenhouse gases emitted in the years to come. The four RCPs (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) are named for the ensuing radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 Watts/m^2, respectively) and are used as input to climate models.

RCP 2.6 was *not* selected because it represents the range of lowest emissions scenarios – in which global GHG emissions peak between 2010-2020 and decline substantially thereafter, resulting in an additional 2.6 W/m^2 of radiative forcing by the end of the 21st century. This pathway would require immediate implementation of stringent climate policies to limit emissions, which, as of 2018, do not appear to be feasible under current political conditions – indeed recent data indicate society remains on the "business-as-usual" trajectory associated with RCP 8.5 (Figure 1 in Fuss et al. 2014). RCP 6.0 was also not selected, as associated projections would most likely be fully bracketed by projections for RCP 4.5 and RCP 8.5, which were selected for downscaling in this study.

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[48] Phase 5 of the COUPLED MODEL INTERCOMPARISON PROJECT (a framework for coupled ocean-atmosphere general circulation models and Earth system models) included a refined estimate for solar irradiation with corrections for scattering and diffraction (Taylor et al. 2012; Scaffetta and Willson 2014).

[49] Accounting for ~80% of climate change projected by the full CMIP5 ensemble suite (PCIC 2014).

[50] ENVIRONMENT CANADA'S ADJUSTED AND HOMOGENIZED CANADIAN CLIMATE DATA (AHCCD) incorporate a number of adjustments applied to the original station data to address non-climatological shifts related to changes in instruments and observation conditions or procedures, thus optimizing their use for climate research (Vincent et al. 2012)

AIR-TO-WATER TEMPERATURE PROJECTIONS

Prospective projections of water temperature conditions in the adult Sockeye freshwater migration corridors were obtained from nonlinear air-to-water temperature relations specific to each index site (e.g. Hyatt et al. 2015). The uncertainty associated with air-to-water statistical regression relations varied within and between sites, due largely to limitations in the water temperature time-series, which were often seasonal, fragmented, and restricted to a few years of observations. Though statistical relations were based on data representing a daily time-step (Mohseni et al. 1998), water temperature data quality ranged from high-resolution hourly time-series recorded on automated datalogger units (e.g. Sproat, Stamp/Somass, Docee, Tahltan), to manual readings obtained 1-6 times per day with a hand-held thermometer (e.g. Meziadin, Babine). Methods often varied within site over subsequent years. Short field operation seasons, yielding less than three months of environmental data, sometimes resulted in data-deficient logistic models that were difficult to parameterize.

In addition, the multi-year statistical regression methods tend to produce predictive models that reasonably estimate average water temperatures, but underestimate extreme temperatures, and above-normal warm years. Historical and future water temperature estimates therefore tend to be 'conservative' for all sites, and likely to underestimate the frequency and duration of days where mean daily water temperatures exceed 19 °C. Therefore, the water temperature data and the models that depend on them should be considered a significant source of error in this analysis, biasing water temperatures and POT Exposure estimators downward.

SOCKEYE INDEX STOCK WATERSHEDS

Site-specific downscaling procedures indicated that air temperatures in all six study watersheds from north to south were projected to rise over the 21st century. Depending on RCP pathway, increases ranged from a minimum of 2-3 °C to a maximum of 4-5 °C during the peak migration months (July-September). These estimates are in keeping with other regional studies (Mote et al. 2003; Mote and Salathé 2009).

Rising air temperatures translated into a range of water temperature increases of 1-2 °C to 3-4 °C, again depending on RCP trajectory, but also on initial site water temperature conditions. Largest increases were associated with sites where initial temperature conditions were lower. Maximum summer water temperature increases of 3-4 °C were projected for northerly watersheds, including Docee (Figure 18), Babine (Figure 22), Meziadin (Figure 26) and Tahltan (Figure 31), which were characterized by cool baseline temperatures (13-16 °C) during the reference period. Projected maximums in water temperature of 17-18 °C would result in a higher frequency and duration of stressful thermal conditions for these stocks than existed in the reference period, but are not expected to occur often enough, or persist long enough (i.e., > 1-2 weeks) to impose a consistent negative impact on Sockeye migrants in the 21st century. For the northern and central stocks, only by the 2080s under the RCP 8.5 trajectory would water temperature conditions approach problematic levels. Until that time, and for all time periods under RCP 4.5, POT Exposure indices indicated negligible water temperature impacts (i.e., $POT_{19\,°C}$ = 3-5 days on average; 75th percentile < 7 days).

The “interior” stock – Babine – unsurprisingly exhibited the highest frequency of dates where air temperatures exceeded 20 °C (Figure 23, top), but, excluding RCP 8.5 estimates in the 2080s (where the mean frequency of $POT_{19\,°C}$ water temperature POT Exposure events approximated 9 dates with a P75 < 13 dates; Figure 23 bottom), these did not translate into numerous or extensive periods of water temperatures exceeding 19 °C (Figure 23 and Figure 25: bottom). Similarly, at the Meziadin site, where $POT_{20\,°C}$ air temperature frequencies were the second highest of the northern and central stocks (Figure 27, top), $POT_{19\,°C}$ water temperature events occurred at less than half the frequencies (Figure 27, bottom). These contrast with Docee (Figure 19) and Tahltan results (Figure 31), for which the frequency of $POT_{20\,°C}$ air temperature dates more closely corresponded to the mean frequency of $POT_{19\,°C}$ water temperature POT Exposures for a given RCP and time-period. Whether these differences are a function of site-specific air/water temperature properties, or a result of inadequate air-to-water temperature conversion models for the Babine and Meziadin retrospective studies (Stiff et al. 2015b,c) as noted above, cannot be resolved without re-analysis using improved water temperature datasets from the latter sites.

Notwithstanding potential concerns over the accuracy of modelled Babine and Meziadin water temperatures, it appears safe to conclude that rising air temperatures are highly unlikely to significantly impact the adult migration life history event of central coast and northern Sockeye index stocks at least through the 2050s under either RCP scenario, given the similarity in monthly mean projected air temperatures amongst the central and northern sites (Table 12, Table 16, Table 20, Table 24). In the event that society continues along the “business-as-usual” GHG emissions path (RCP 8.5), these stocks will begin to experience freshwater migration delays of 7-10 days on a regular basis (75% of projections) with site maximums of 14-22 days (Figure 21, Figure 25, Figure 29, Figure 33).

The southerly watersheds (Somass and Sproat) were already characterized by thermal conditions near the upper bounds of Sockeye tolerance levels for some proportion of each migration period (Figure 13). Monthly mean air temperatures in the watershed appear set to exceed 20-21 ± 3 °C in both July and August by the 2050s, regardless of emissions scenario (Table 2).

Both Great Central-bound and Sproat-bound Sockeye stocks migrate up the Somass River, from June to September, with the bulk of migration in July and August (Hyatt et al. 2015). Somass River water temperatures for July-August, currently averaging 19-20 °C (1971-2000), were projected to increase a further 1-2 °C by the 2080s, reaching 21-22 °C depending on RCP (Figure 13, Table 2, Table 7). The frequency of dates for which Somass mean daily water temperatures exceed 19 °C, currently averaging about 47 days in the season, was projected to approach monthly maximums during peak migration in the 2050s (Figure 15, Table 5).

The middle 50th percentile of all model outcomes indicated a potential range of 75-96 days per year presenting a thermal barrier to Somass migration by the 2050s (Figure 14), equivalent to 62-79% of the entire 122-day migratory period from June to September. The mean continuous duration of thermal barrier events was projected to rise by a week for each time-period, from 13 days on average during the reference period, to 19-20 days by the 2020s, and 27-33 days by the 2050s (Figure 17). Under the RCP 8.5 scenario, the duration of thermal barriers could reach 55 ± 15 days in length, on average, by the 2080s, with an all-model P75 of 63 days, or over 2 months (Table 8), which is an unsustainable length of time for Sockeye to delay. Realistically, however, without some form of mitigation (e.g. cold-water releases; Lill, Wightman and Olsen 2012), Somass Sockeye stocks would likely already be extirpated by that point in time due to the 4-week-average delay impacts projected here for the 2050s.

For Sproat-bound fish, Sproat River temperature conditions accrue to adult migrants subsequent to, and therefore in addition to, Somass impacts. Sproat River water temperatures, currently averaging ~20 ± 2 °C during peak migration for the reference period, may average 22-24 °C by the end of the century (Table 3, Figure 13). The frequency of dates for which mean daily water temperatures exceed 19 °C were estimated to approach monthly maximums during peak migration as early as the 2020s (Figure 16), and increasingly occur in June and September, affecting early and late components of the Sproat run. Potential thermal barrier frequencies of 100% of July and August, and 86-93% of the entire migratory season, were projected for the 2050s (Table 6). The mean duration of thermal barrier events in Sproat River, averaging 27 ± 3 days during the reference period, could average 41 days by the 2020s, 51-56 days by the 2050s (depending on RCP) and 58-83 days by the 2080s (Table 9). The lowest estimate for the 'best-case scenario' (RCP 4.5) indicated a minimum of 31 days as the average duration of Sproat River $POT_{19\,°C}$ events in the 2020s (Figure 17).

If Sproat Sockeye halted migration in response to $POT_{19\,°C}$ thermal conditions, the stock would likely be extinct sometime in the 2020s. However, it is unclear whether Sproat-bound fish actually halt migration at the Sproat River tributary (i.e., seek cold-water refugia and hold, or retreat to marine waters) once they have entered the Somass system, regardless of how elevated Sproat River water temperatures may be. Tag studies suggest the decision to commence upstream migration may be made by Sockeye in the lower Somass estuary, and may be, to some degree, 'irreversible' (Pellett et al. 2015). Thus the Sproat $POT_{19\,°C}$ 'potential thermal barrier' indicator may not actually indicate Sproat Sockeye migration stoppage, though biological impacts at temperatures above 19 °C may still delay migrants via stress, injury, disease, or reduced aerobic capacity. Fortunately, the Sproat River is a short ascent (2-3 km) and, evidently (from numerous field observations) can be endured by the fish if they are not overly debilitated by downstream conditions.

CONCLUSION

Site-specific downscaled GCM data indicated that air temperatures in six Sockeye watersheds are projected to rise during peak migration months (July-September). Air temperature increases over the 21st century ranged from a minimum of 2-3 °C to a maximum of 4-5 °C, depending on RCP scenario. These projected changes translated into maximum mean water temperatures of 17-18 °C for central and northern watersheds, including Tahltan, Meziadin, Babine, and Docee, which were characterized by cool baseline temperatures (13-16 °C) during the reference period. In southern watersheds, water temperatures were projected to exceed Sockeye thermal tolerance levels for adult migration (19 °C) for >80% of the time during peak migration months by the 2020s in Sproat River and by the 2050s in Somass River, regardless of RCP.

The implications for the central and northern Sockeye index stocks are neutral or negligible thermal disruption for adult freshwater migrants. The implications for Somass and Sproat stocks are a high likelihood of significant and repeated disruptions to freshwater migrant populations as early as the 2020s, including frequent and lengthy (multi-week to month-long) delays in migration, which will exacerbate the usual suite of thermal impacts on fish such as stress, disease, and pre-spawn mortality (e.g. Hyatt et al. 2015). These projections do not auger well for sustainable production of Somass Sockeye salmon stocks. Unless abated, direct and indirect thermal impacts, in conjunction with climate-induced hydrological changes, will reduce Sockeye habitat, health and abundance, and ultimately lead to serial reproductive failures, with a high likelihood of commercial extinction, if not extirpation, of one or both Somass stocks by 2050. Given such a future, further human interventions (e.g. additional water storage, engineering of "cold-water" release structures for the Somass, Stamp and Sproat rivers) will be necessary to mitigate for trends in environmental conditions that, left unaddressed, will most certainly decrease future migration success of adult Sockeye salmon in the Somass River system.

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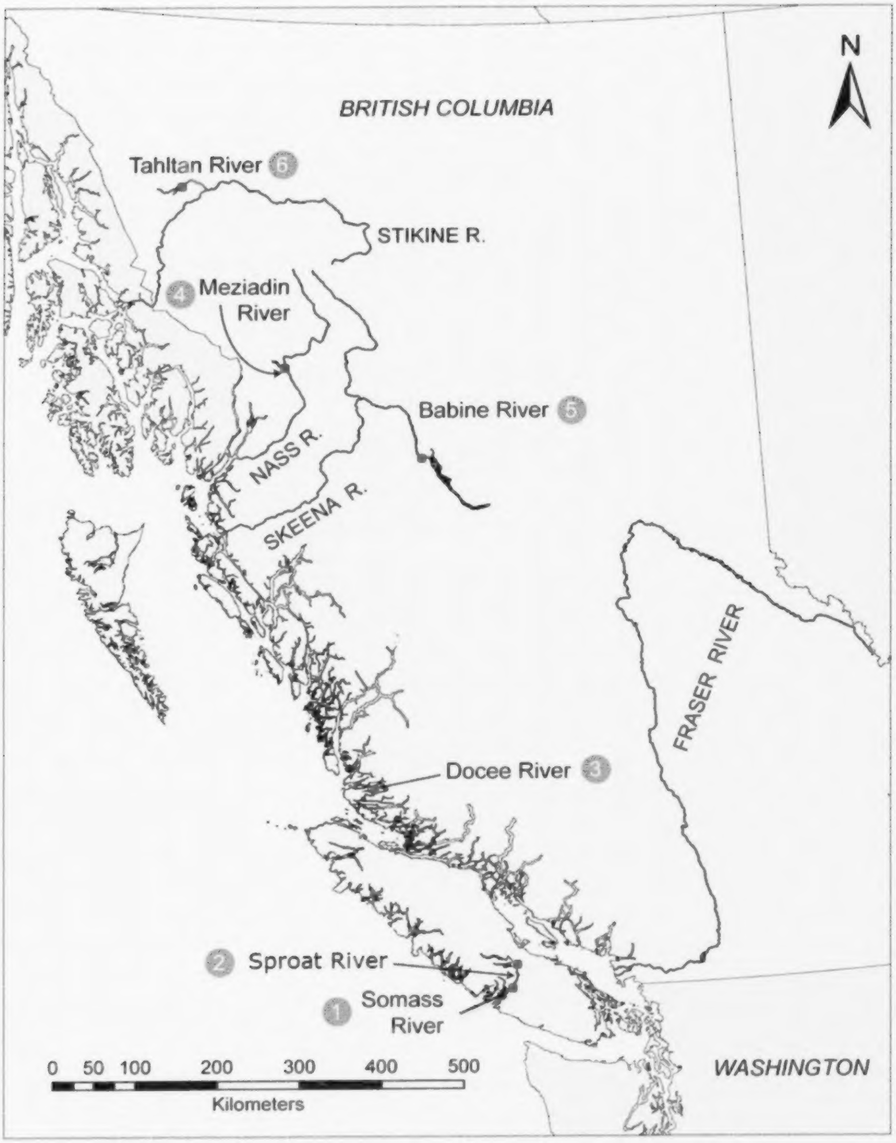
N
BRITISH COLUMBIA
Tahltan River 6
STIKINE R.
4 Meziadin River
Babine River 5
NASS R.
SKEENA R.
FRASER RIVER
Docee River 3
2 Sproat River
1 Somass River
0 50 100 200 300 400 500
Kilometers
WASHINGTON

Figure 1. Sockeye salmon indicator stocks freshwater migration corridors.

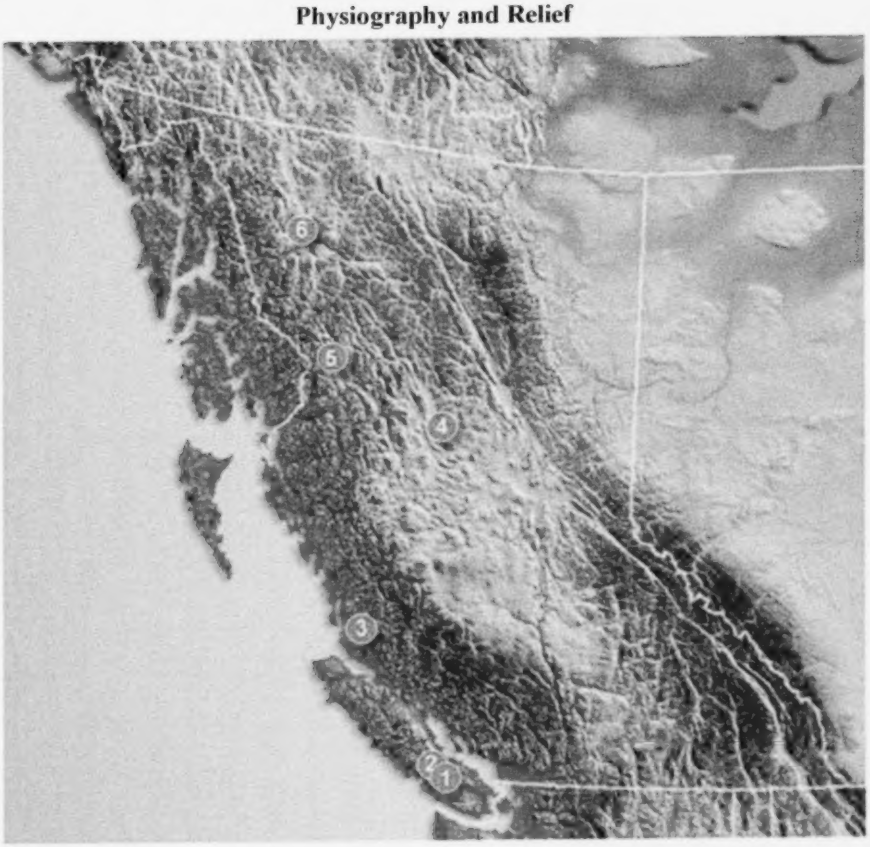

Figure 2. Terminal locations of Sockeye salmon index stocks freshwater migration corridors associated with temperature analysis and future climate projections (Wikipedia):

(1) Somass River (WCVI, South Coast)
(2) Sproat River: (WCVI, South Coast)
(3) Docee River (Central Coast)
(4) Babine River (Skeena watershed, North Coast)
(5) Meziadin River (Nass watershed, North Coast)
(6) Tahltan River (Stikine watershed, Transboundary Region)

Köppen Climate-Type Classification

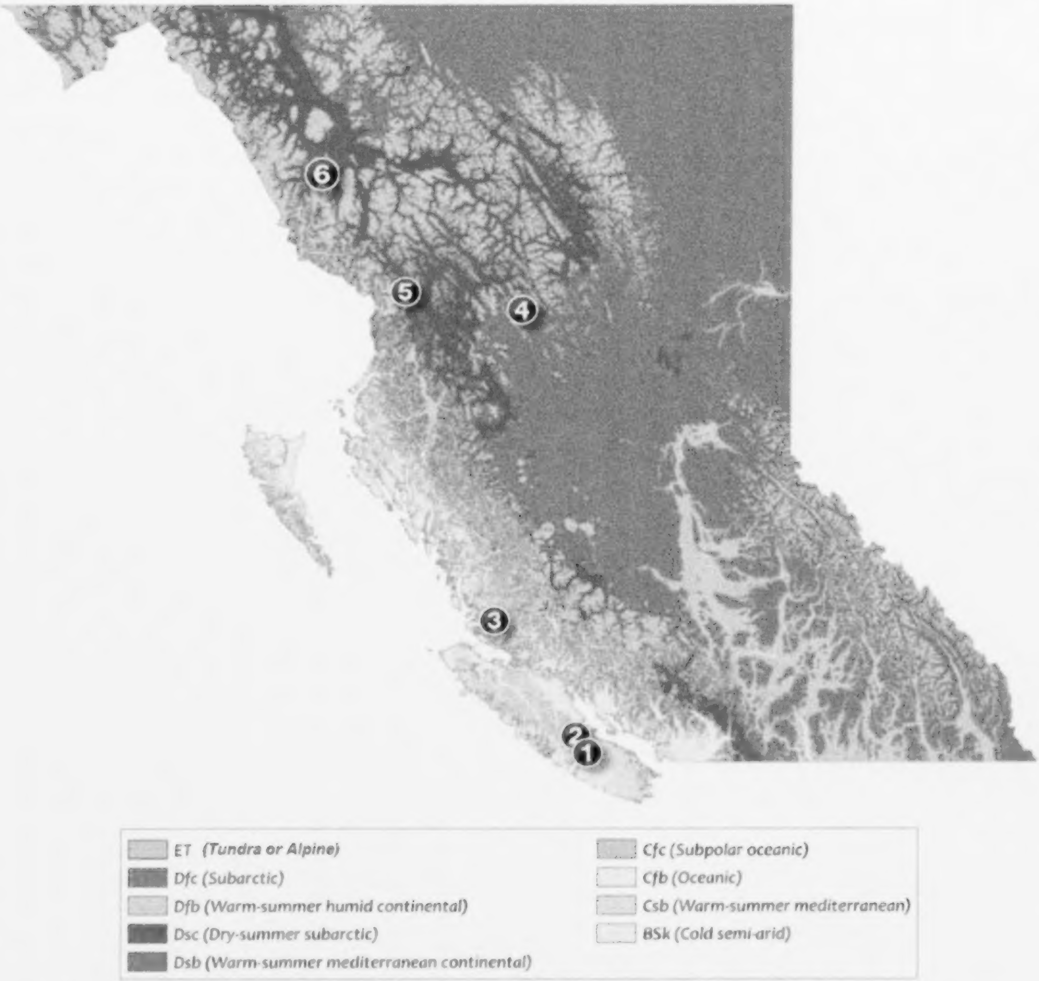
6
5
4
3
2
1
ET (Tundra or Alpine)
Dfc (Subarctic)
Dfb (Warm-summer humid continental)
Dsc (Dry-summer subarctic)
Dsb (Warm-summer mediterranean continental)
Cfc (Subpolar oceanic)
Cfb (Oceanic)
Csb (Warm-summer mediterranean)
BSk (Cold semi-arid)

Figure 3. Terminal locations of Sockeye salmon index stocks freshwater migration corridors, and associated Köppen climate type ecosystems of B.C. (Peel et al. 2007)[51]

(1) Somass River: *Oceanic* (*Cfb*)
(2) Sproat River: *Oceanic* (*Cfb*)
(3) Docee River: *Oceanic* (*Cfb*)
(4) Babine River: *Subarctic* (*Dfc*)
(5) Meziadin River: *Dry Summer Subarctic (Dsc)*
(6) Tahltan River: *Dry Summer Subarctic* (*Dsc*)

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[51] Source graphic: A. Peterson [CC BY-SA 4.0] via Wikimedia Commons.

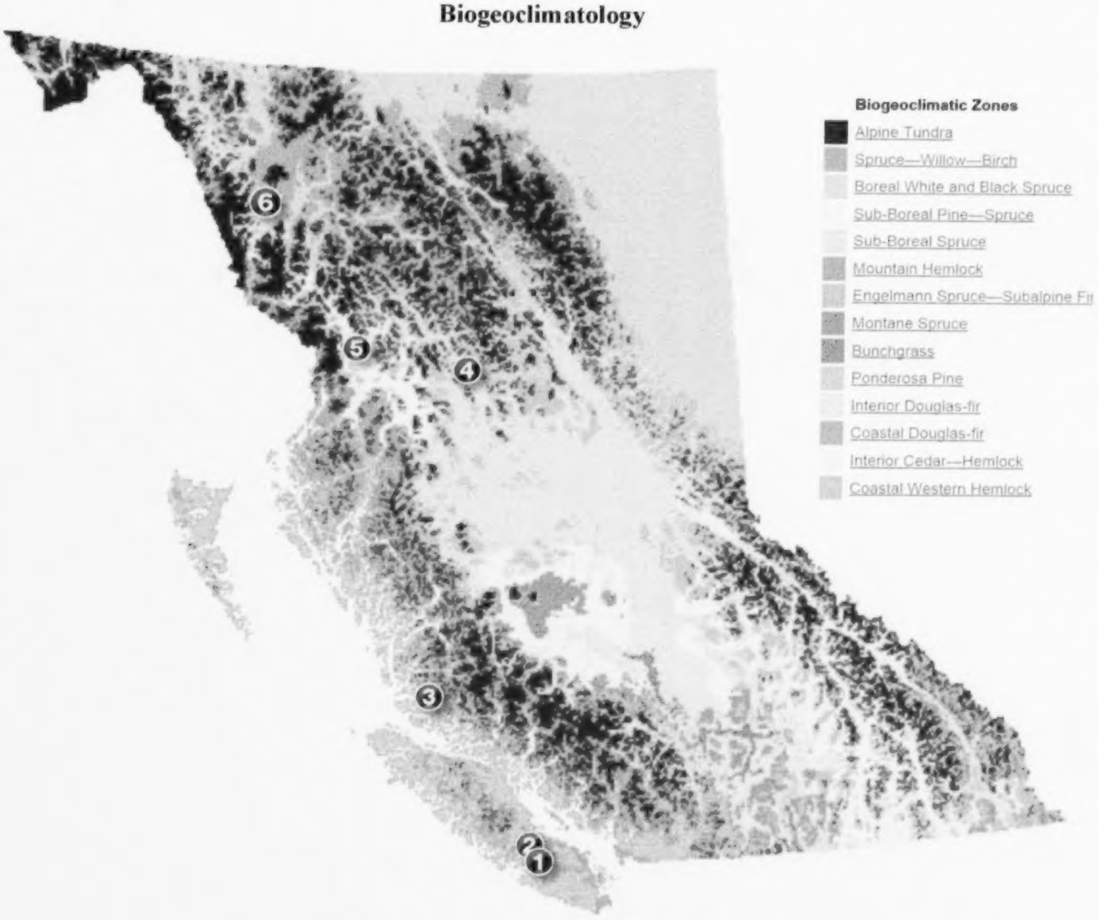
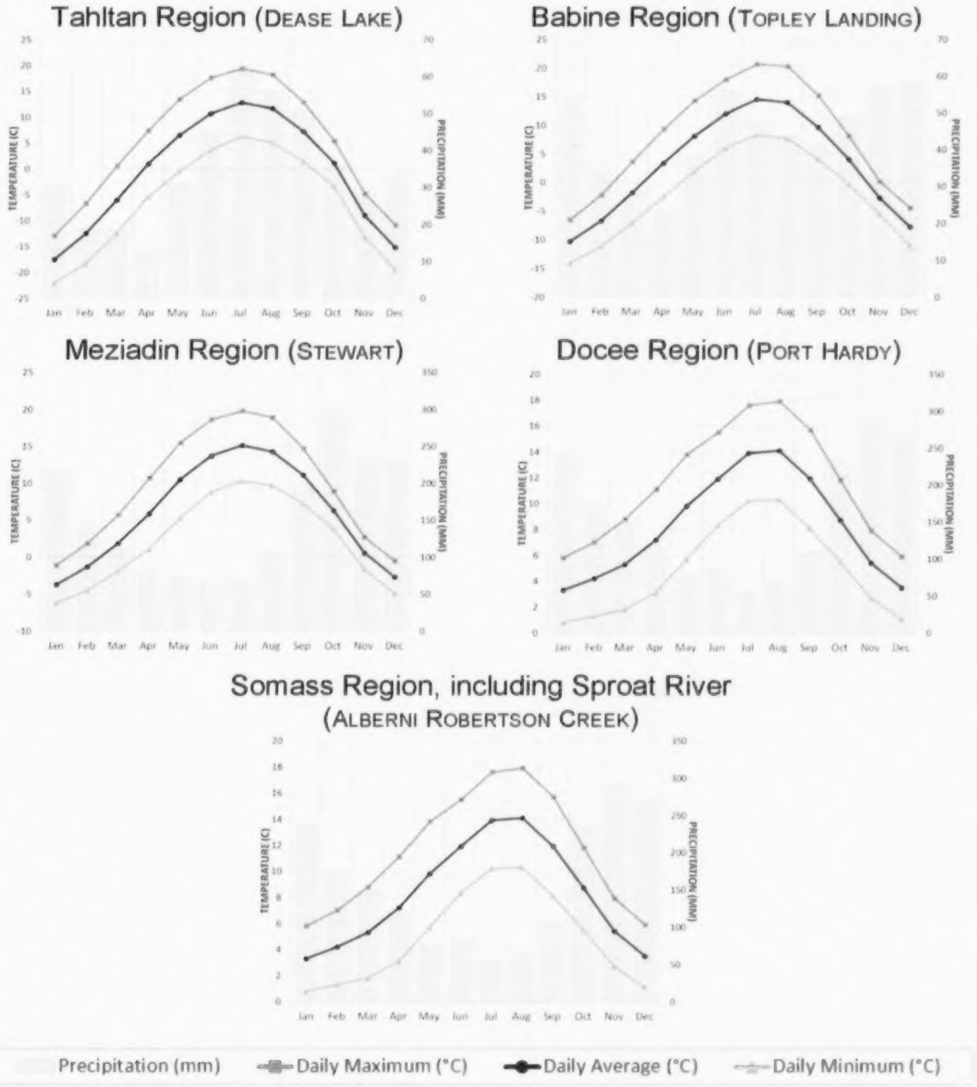

Biogeoclimatology
Biogeoclimatic Zones
Alpine Tundra
Spruce—Willow—Birch
Boreal White and Black Spruce
Sub-Boreal Pine—Spruce
Sub-Boreal Spruce
Mountain Hemlock
Engelmann Spruce—Subalpine Fir
Montane Spruce
Bunchgrass
Ponderosa Pine
Interior Douglas-fir
Coastal Douglas-fir
Interior Cedar—Hemlock
Coastal Western Hemlock
6
5
4
3
2
1

Figure 4. Terminal locations of Sockeye salmon index stocks freshwater migration corridors, and associated biogeoclimatic zones (Source: B.C. Ministry of Forests):

(1) Somass River: Coastal Western Hemlock
(2) Sproat River: Coastal Western Hemlock
(3) Docee River: Coastal Western Hemlock
(4) Babine River: Sub-Boreal Spruce
(5) Meziadin River: Interior Cedar - Hemlock
(6) Tahltan River: Boreal White – Black Spruce

Regional Climatology



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2. Babine region, based on Topley Landing Station 1078209 (elev. 722 m)
3. Meziadin region, based on Stewart Station 1067742 (elev. 7 m)
4. Docee region, based on Port Hardy Station 1026270 (elev. 22 m)
5. Somass / Sproat region, Alberni Robertson Creek Station 1090230 (elev. 74 m)

River Hydrography

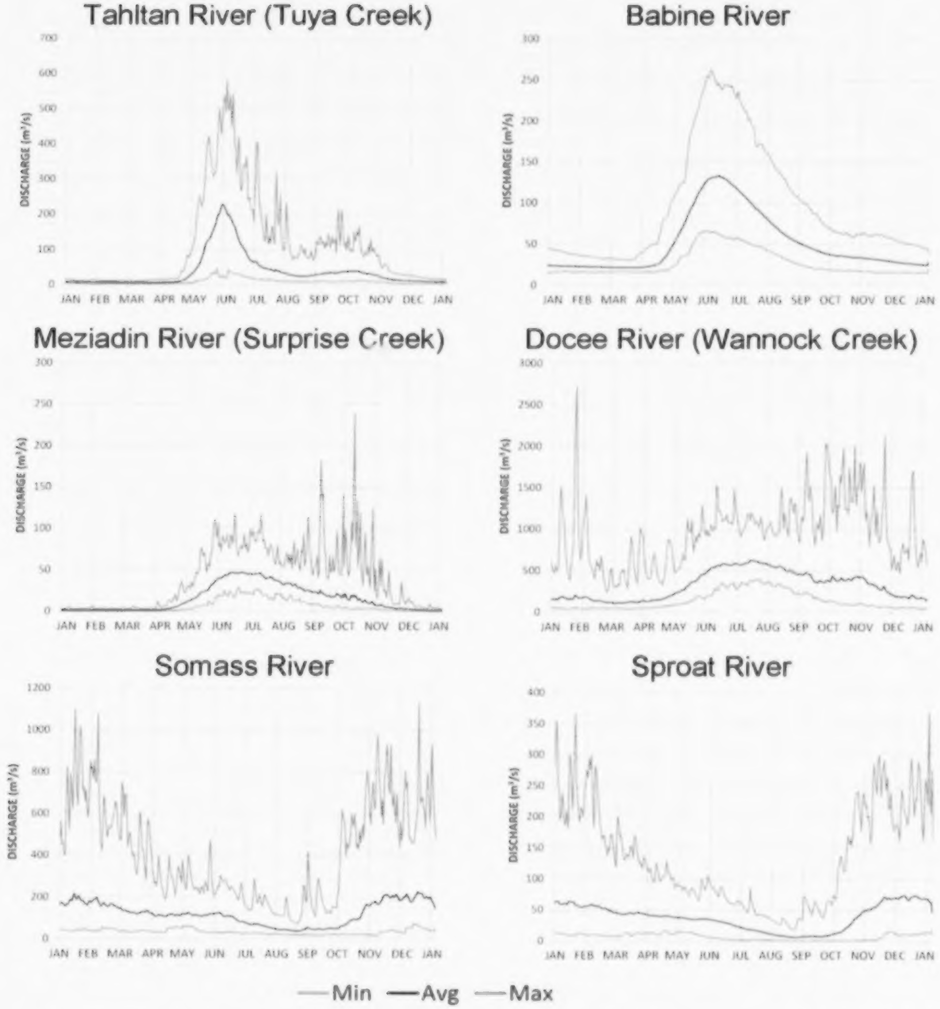
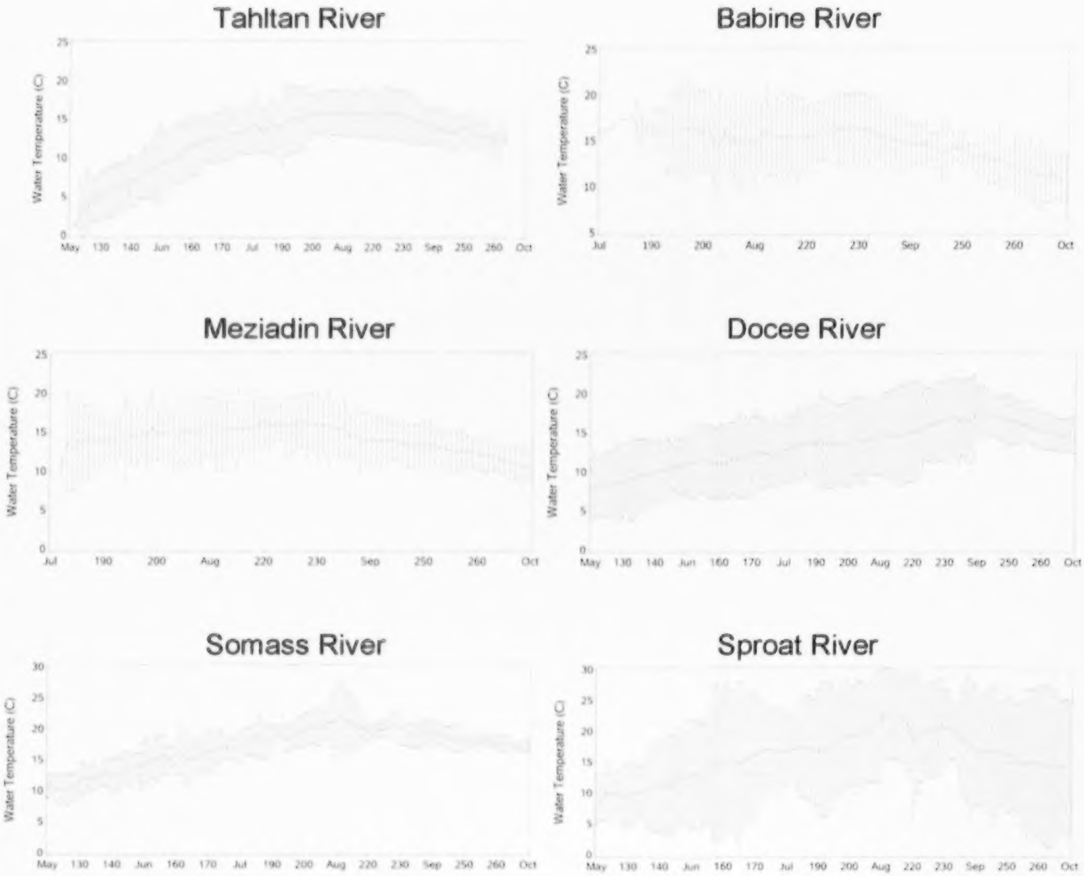


Figure 6. Hydrological minimum, mean, and maximum daily discharge for Sockeye Salmon index stock freshwater migration corridors (Source: Archived hydrometric data, Environment Canada and Climate Change):

- Tahltan River (proxy data: Tuya Creek 08CD001, 1962-2013): *Nivo-pluvial*
- Babine River (08EC013, 1972-2016): *Nivo-glacial*
- Meziadin River (proxy data: Surprise Creek 08DA005, 1967-2014): *Pluvio-Nival*
- Docee River (proxy data: Wannock Creek 08FA002, 1927-2015): *Pluvio-Nival*
- Somass River (08HB017, 1957-2002): *Pluvial*
- Sproat River (08HB008, 1913-2013): *Pluvial*
(*River regimes:* https://en.wikipedia.org/wiki/River_regime)

River Thermography



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- Tahltan River, 1962-2013 (Stiff et al. 2013)
- Babine River, 2003-2014 (Stiff et al. 2015a)
- Meziadin River, 1998-2012 (Stiff et al. 2015c)
- Docee River, 2004-2008 (Stiff et al. 2015b)
- Somass River, 1991-2012 (Hyatt et al. 2015)
- Sproat River, 1996, 2000-2002, 2009-2012 (Hyatt et al. 2015)

Somass (WCVI) Watershed

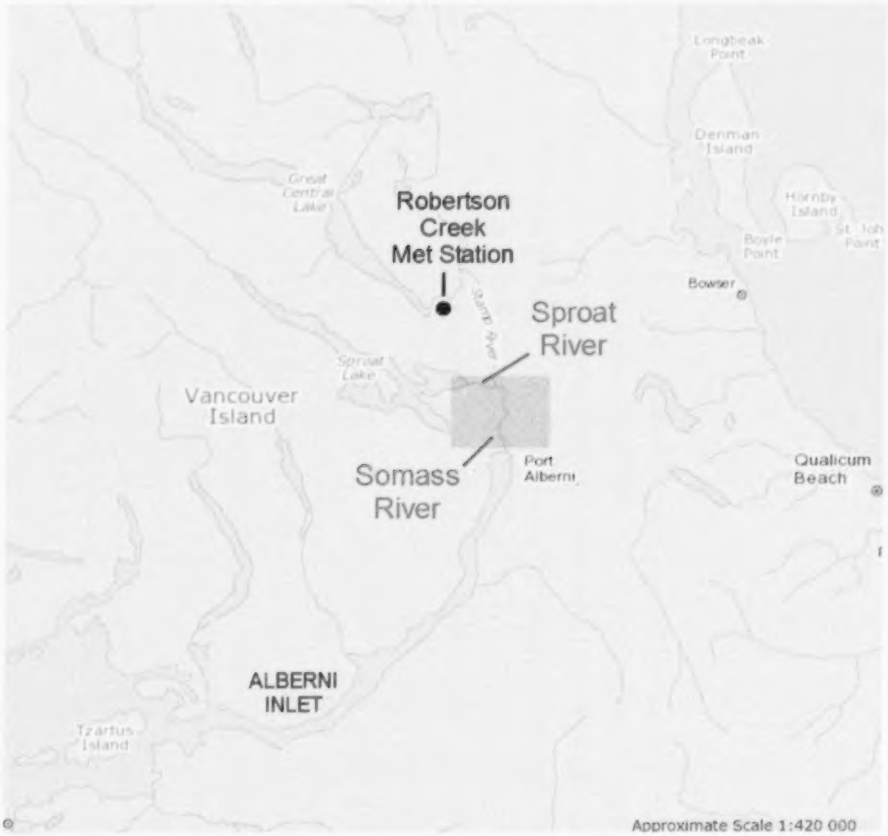
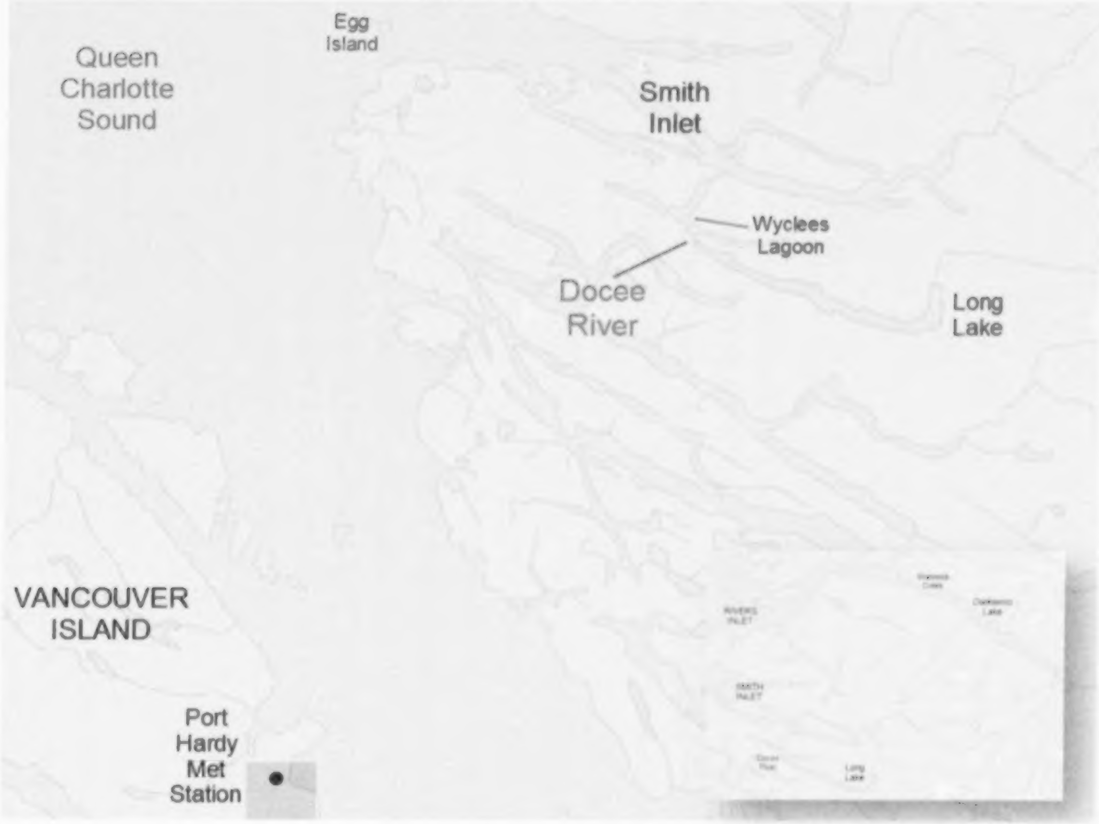

Longbeak Point
Denman Island
Hornby Island
Boyle Point
St. John Point
Bowser
Great Central Lake
Robertson Creek Met Station
Stamp River
Sproat River
Sproat Lake
Vancouver Island
Somass River
Port Alberni
Qualicum Beach
ALBERNI INLET
Tzartus Island
Approximate Scale 1:420 000

Figure 8. Somass River and Sproat River near Port Alberni, B.C. Red highlighted area corresponds to grid-points for statistically-downscaled GCM scenario data downloaded, near Robertson Creek meteorological station. (Adapted from: NRCAN Atlas of Canada 2018; Licence)



Docee (Long Lake) Watershed

Egg Island
Queen Charlotte Sound
Smith Inlet
Wyclees Lagoon
Docee River
Long Lake
VANCOUVER ISLAND
Port Hardy Met Station

Figure 9. Location of PORT HARDY meteorological station and Docee River in the Long Lake watershed. Red highlighted area corresponds to grid-points for statistically-downscaled GCM scenario data downloaded, near PORT HARDY meteorological station. (Adapted from: NRCAN Atlas of Canada 2018; Licence)

Babine (Skeena) Watershed

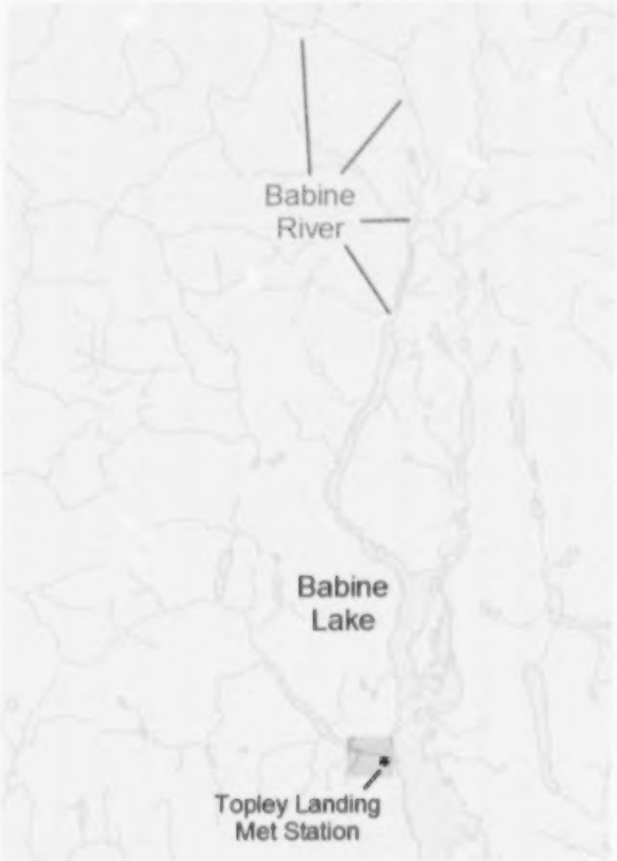

Babine River
Babine Lake
Topley Landing Met Station

Figure 10. Location of TOPLEY LANDING meteorological station and Babine River in the Skeena watershed. Red highlighted area corresponds to grid-points for statistically-downscaled GCM scenario data downloaded from PCIC data portal, corresponding to TOPLEY LANDING meteorological station. (Adapted from: NRCAN Atlas of Canada 2018; Licence)

Meziadin (Nass) Watershed

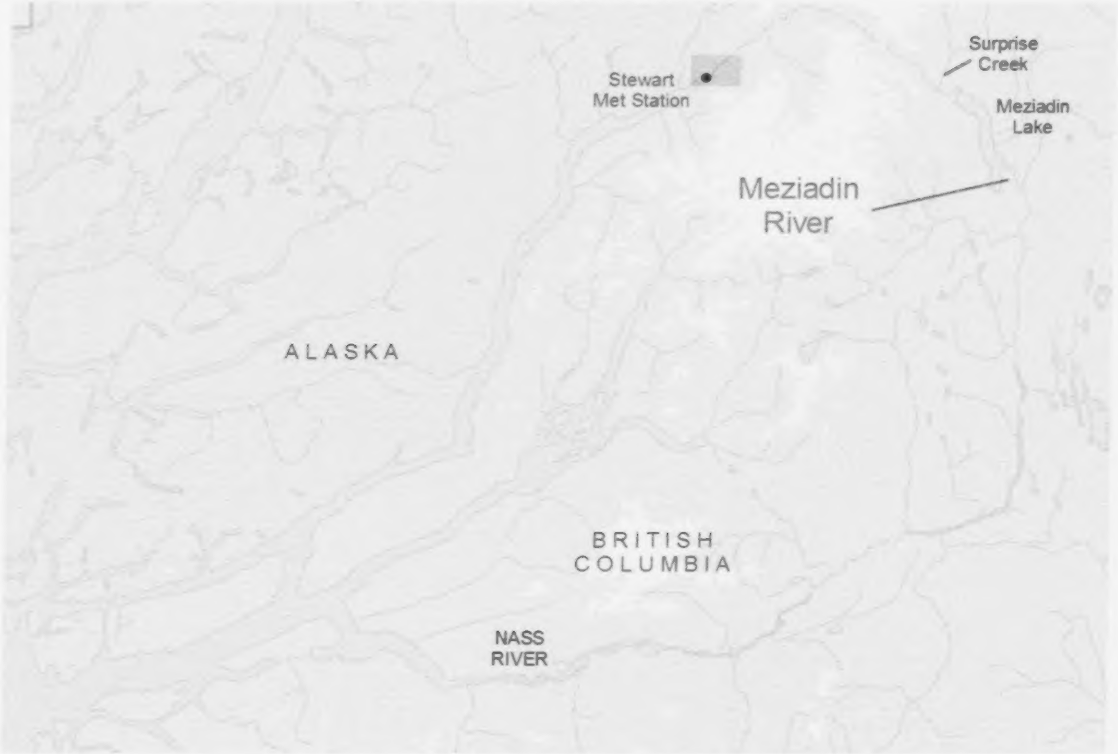

Stewart
Met Station
Surprise
Creek
Meziadin
Lake
Meziadin
River
ALASKA
BRITISH
COLUMBIA
NASS
RIVER

Figure 11. Location of STEWART meteorological station and Meziadin River in the Nass watershed. Highlighted area corresponds to grid-points for statistically-downscaled GCM scenario data downloaded from PCIC data portal, corresponding to STEWART meteorological station. (Adapted from: NRCAN Atlas of Canada 2018; Licence)

Tahltan (Stikine) Watershed

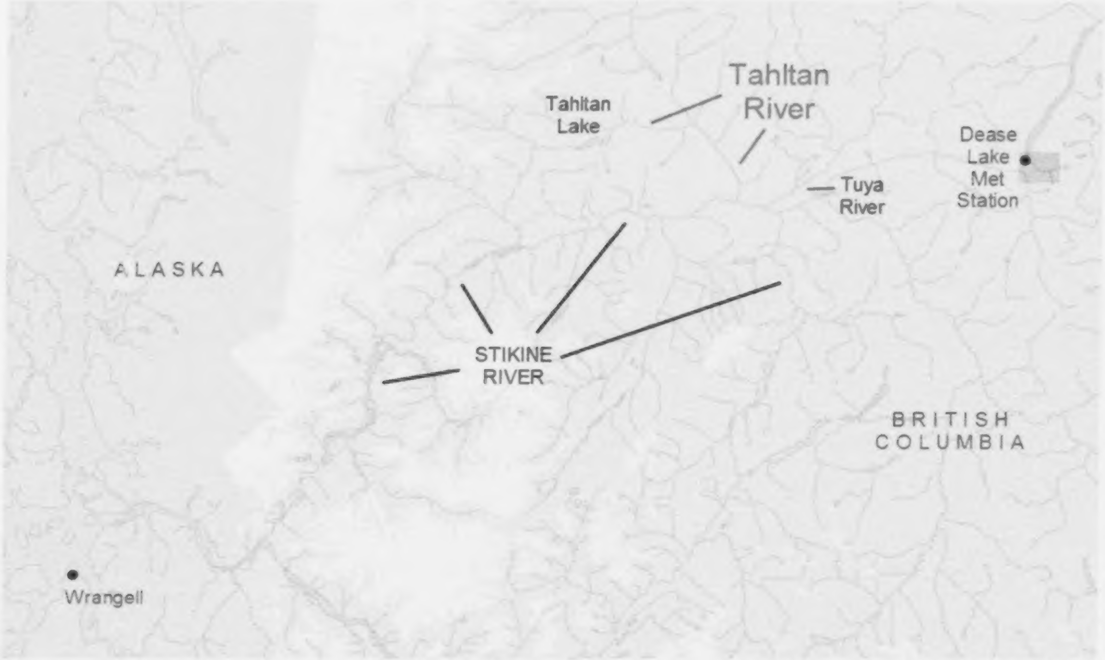

Tahltan Lake
Tahltan River
Dease Lake Met Station
Tuya River
ALASKA
STIKINE RIVER
BRITISH COLUMBIA
Wrangell

Figure 12. Location of DEASE LAKE meteorological station and Tahltan River in the Stikine watershed. Highlighted area corresponds to grid-points for statistically-downscaled GCM scenario data downloaded from PCIC data portal, corresponding to DEASE meteorological station. (Adapted from: NRCAN Atlas of Canada 2018; Licence)

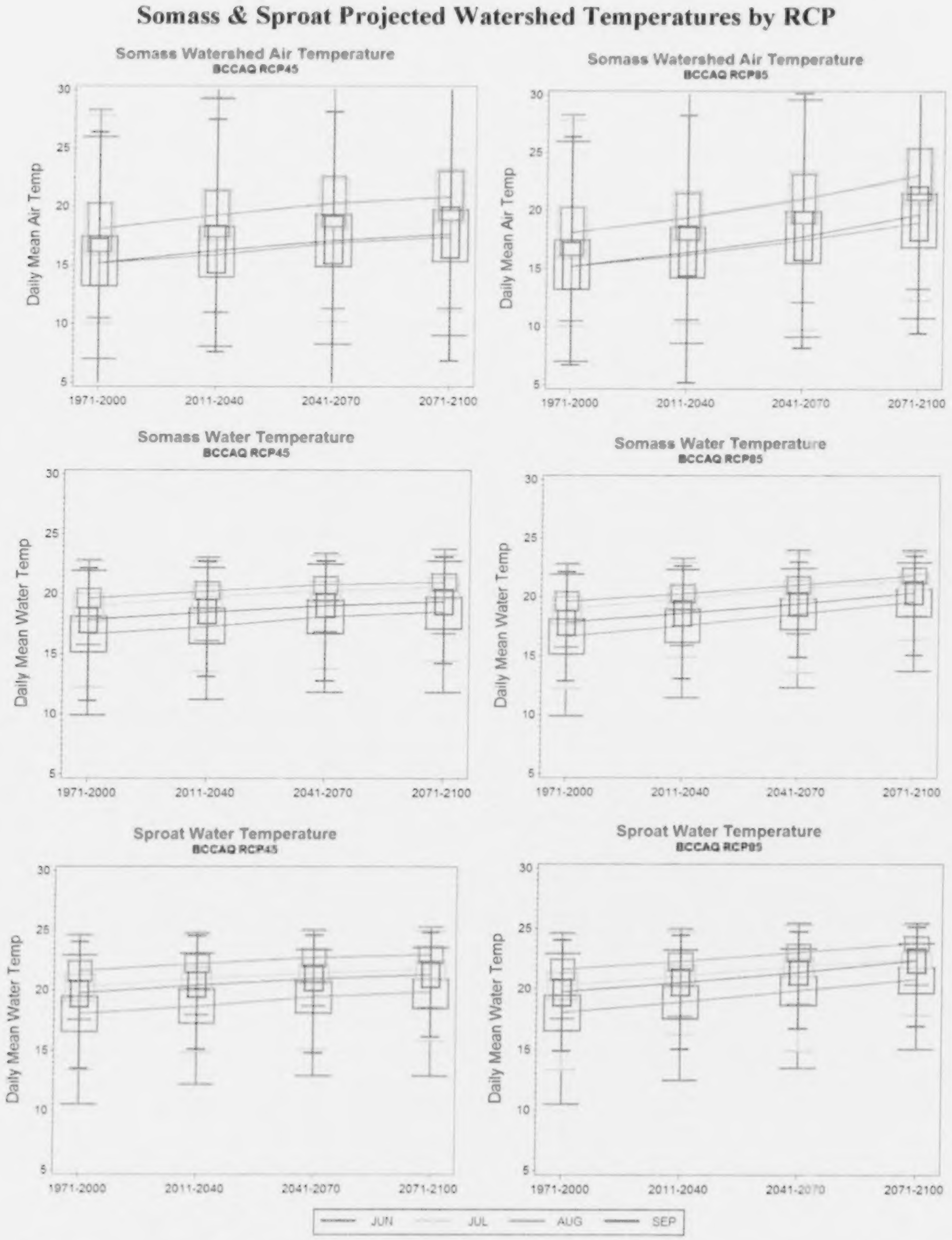


Figure 13. Trends in projected monthly Somass watershed air temperature (median, quartiles and range) and Somass and Sproat water temperature, by month, across all BCCAQ GCM models and years within time-period (RCP 4.5, left; RCP 8.5, right).

Somass & Sproat Watershed Projected POT Dates by RCP

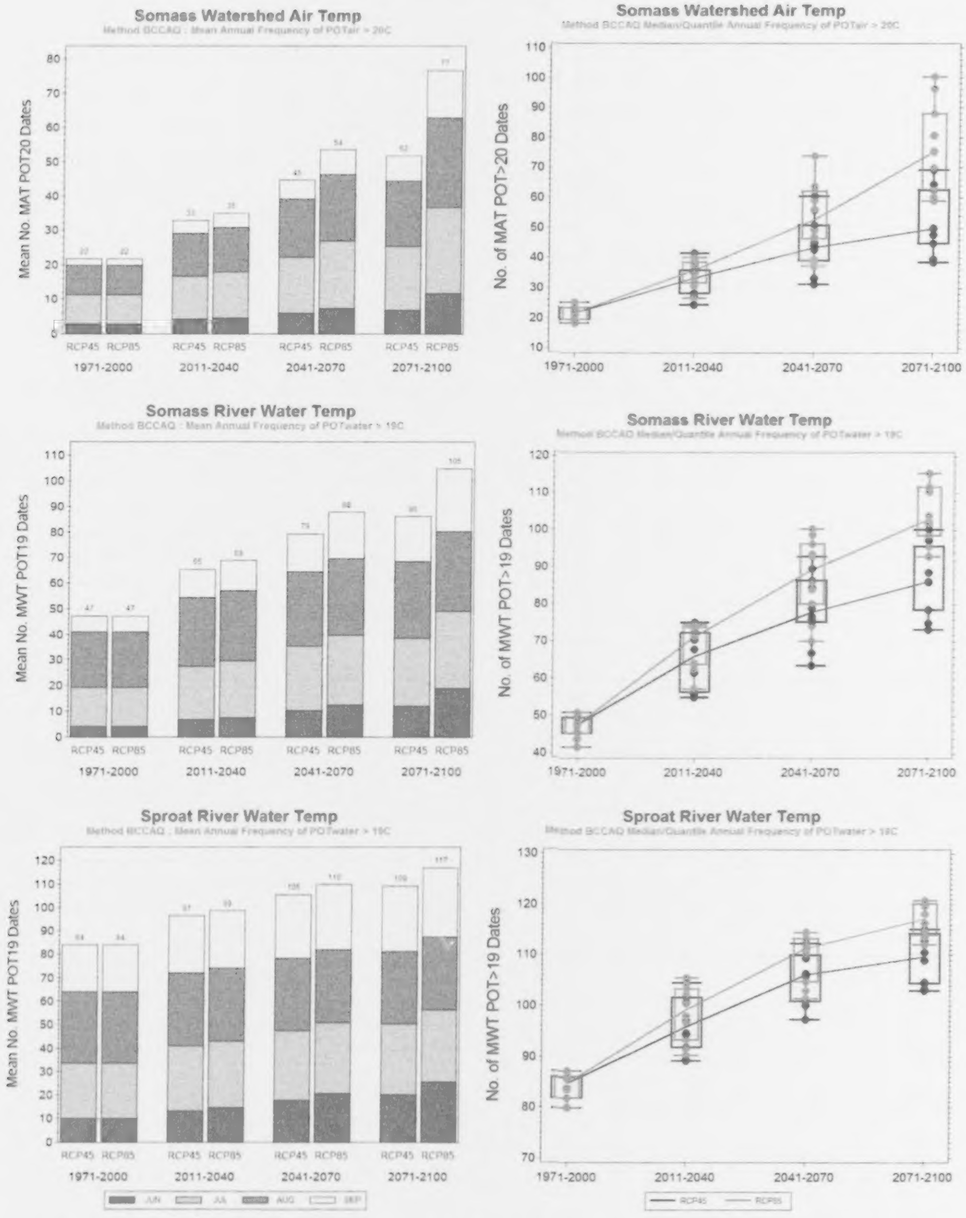


Figure 14. Projected POT events (mean number of dates exceeding threshold temperature) for regional air temperature (top), Somass water temperature (middle) and Sproat water temperature (bottom). Bar charts indicate mean frequency of POT events by time-period, RCP scenario and month of year (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for frequency of POT events.

Somass Water Temperature – Projected POT$_{19°C}$ Dates By Month

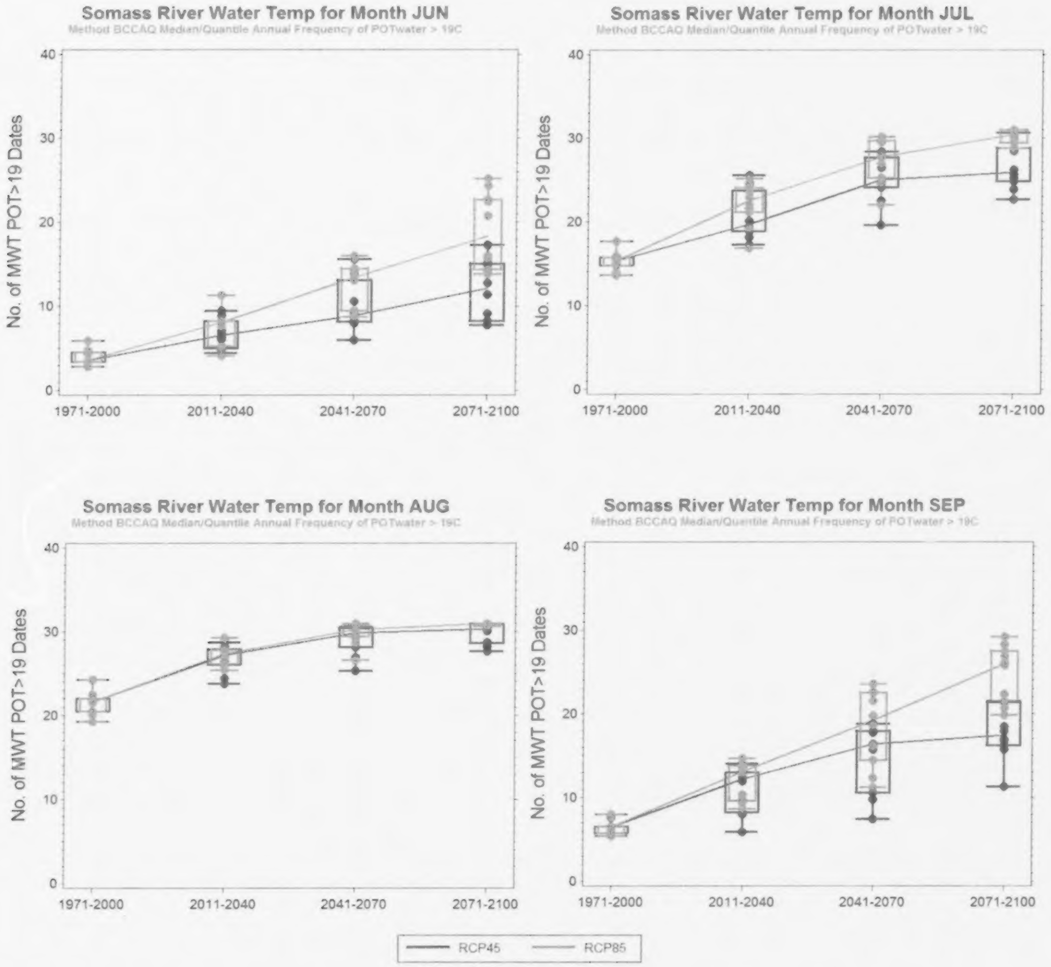


Figure 15. Mean annual frequency of POT temperature events for Somass River water temperature across all models and years by RCP, time-period, by month: June to September.

Sproat Water Temperature – Projected $\text{POT}_{19°\text{C}}$ Dates By Month

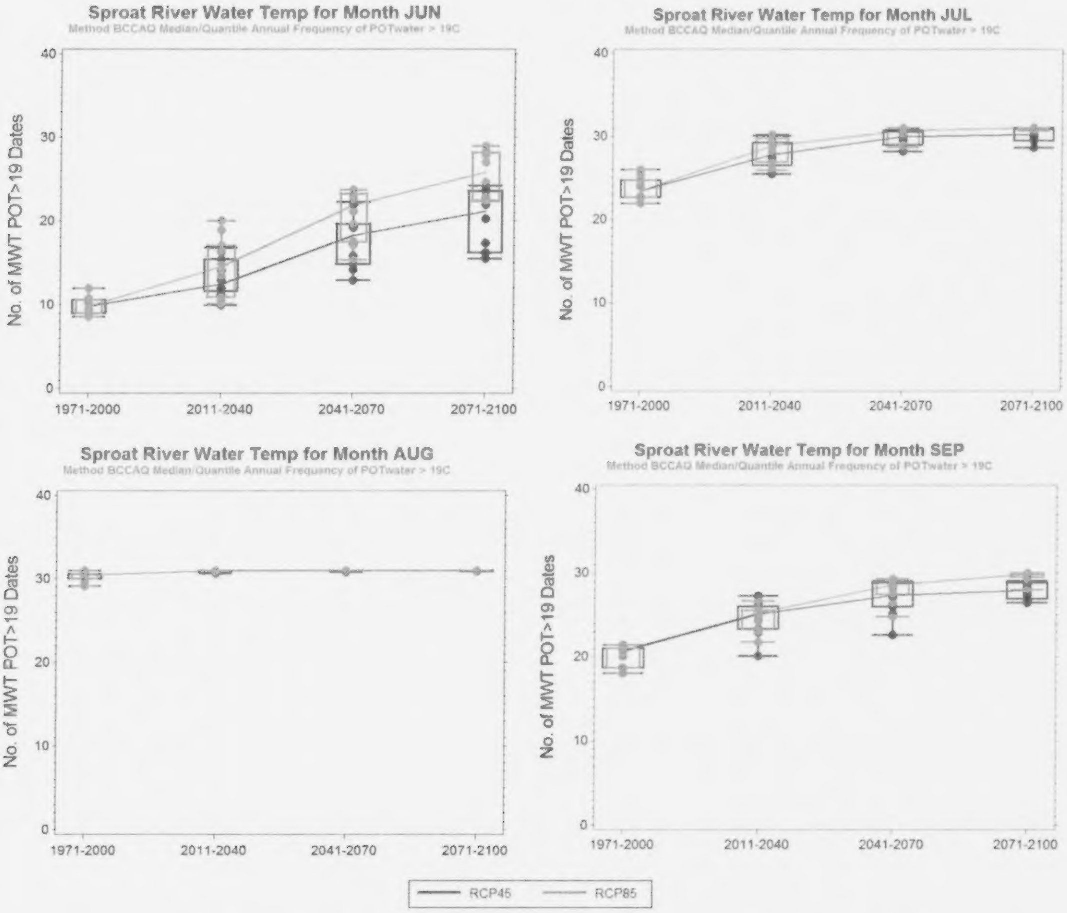


Figure 16. Mean annual frequency of POT temperature events for Sproat River water temperature across all models and years by RCP, time-period, by month: June to September.

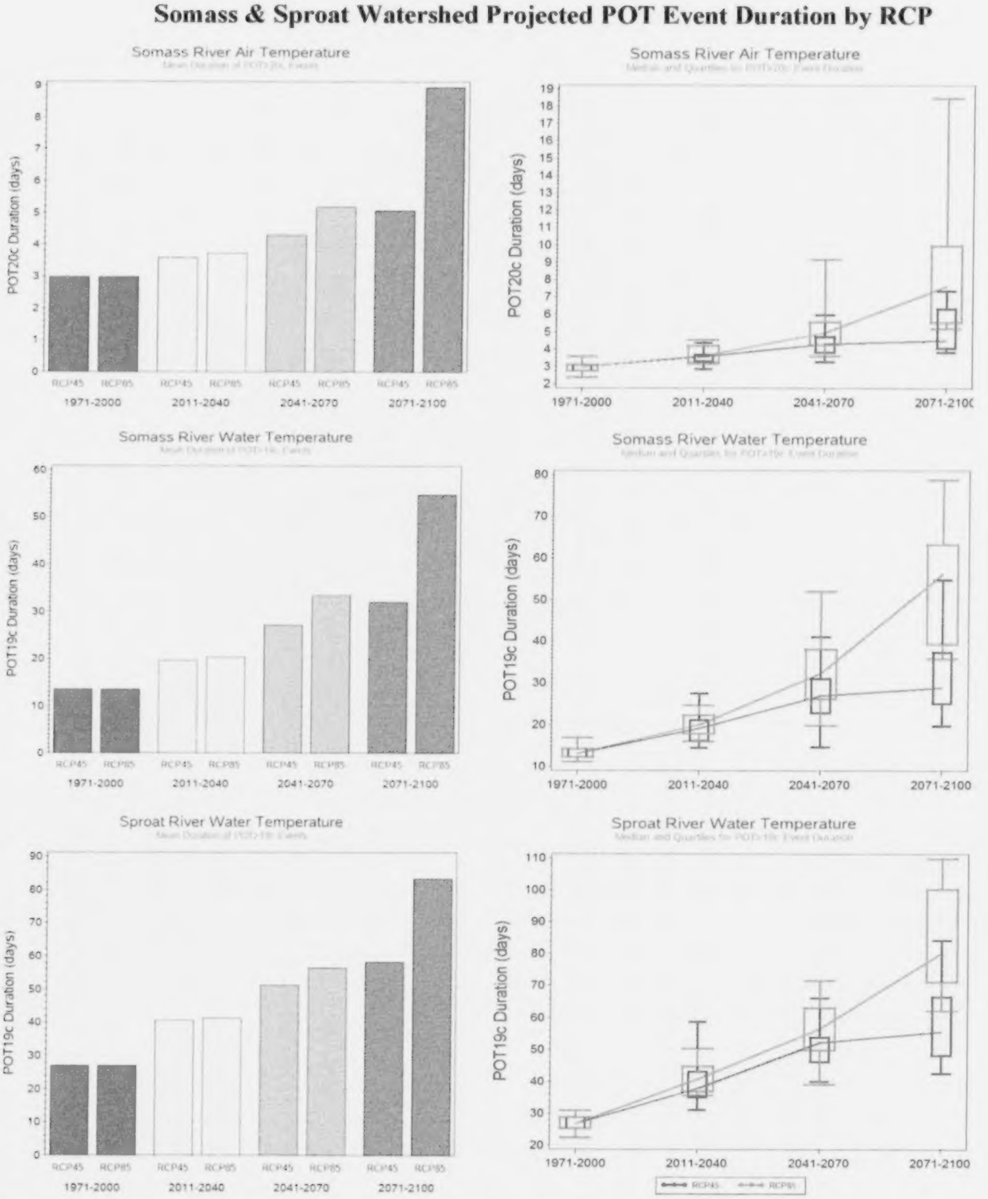


Figure 17. Projected POT continuous duration (mean number of continuous days exceeding threshold temperature) for regional air temperature (top), Somass water temperature (middle) and Sproat water temperature (bottom). Bar charts indicate mean duration of POT events by time-period, RCP scenario (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for POT event duration.

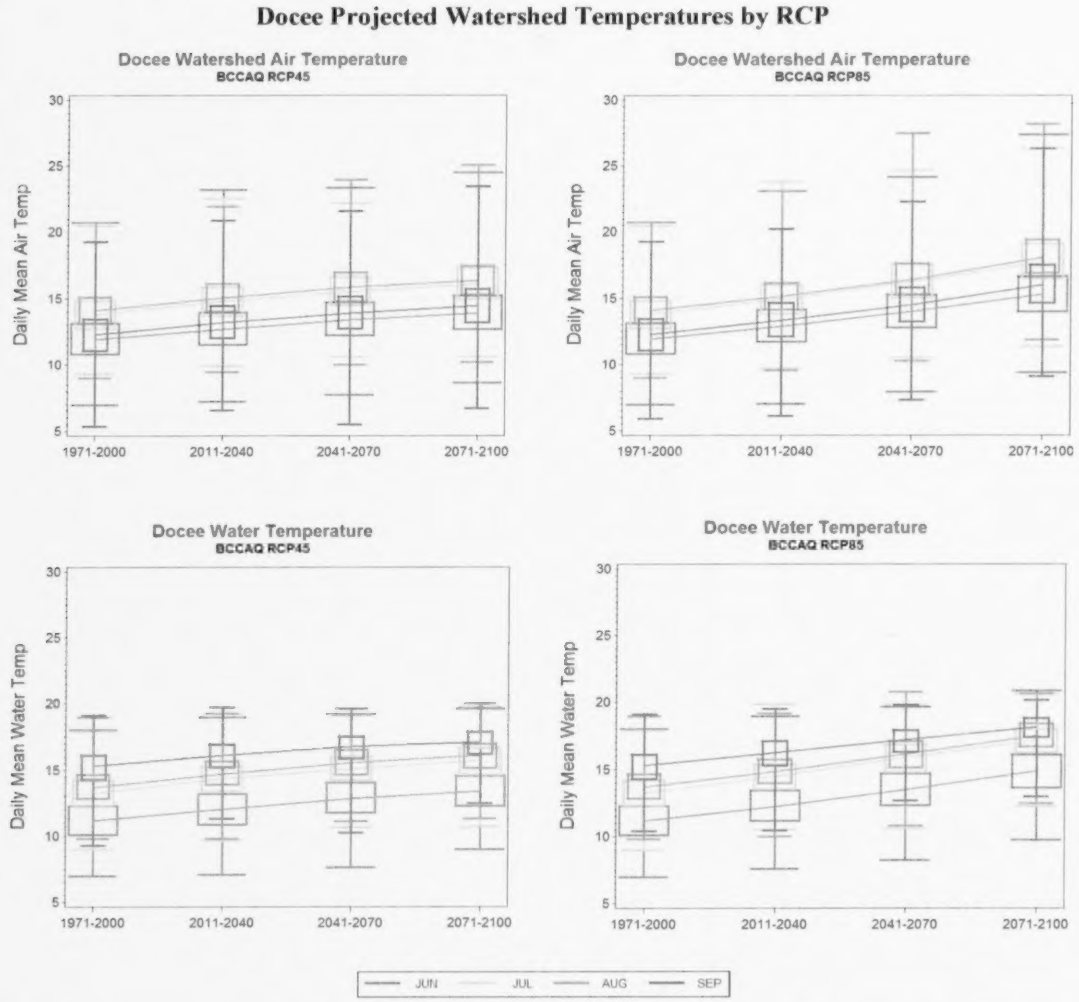


Figure 18. Trends in projected monthly regional watershed air temperature (median, quartiles and range) and Docee River water temperature, by month, across all BCCAQ GCM models and years within time-period (RCP 4.5, left; RCP 8.5, right).

Docee Watershed Projected POT Dates by RCP

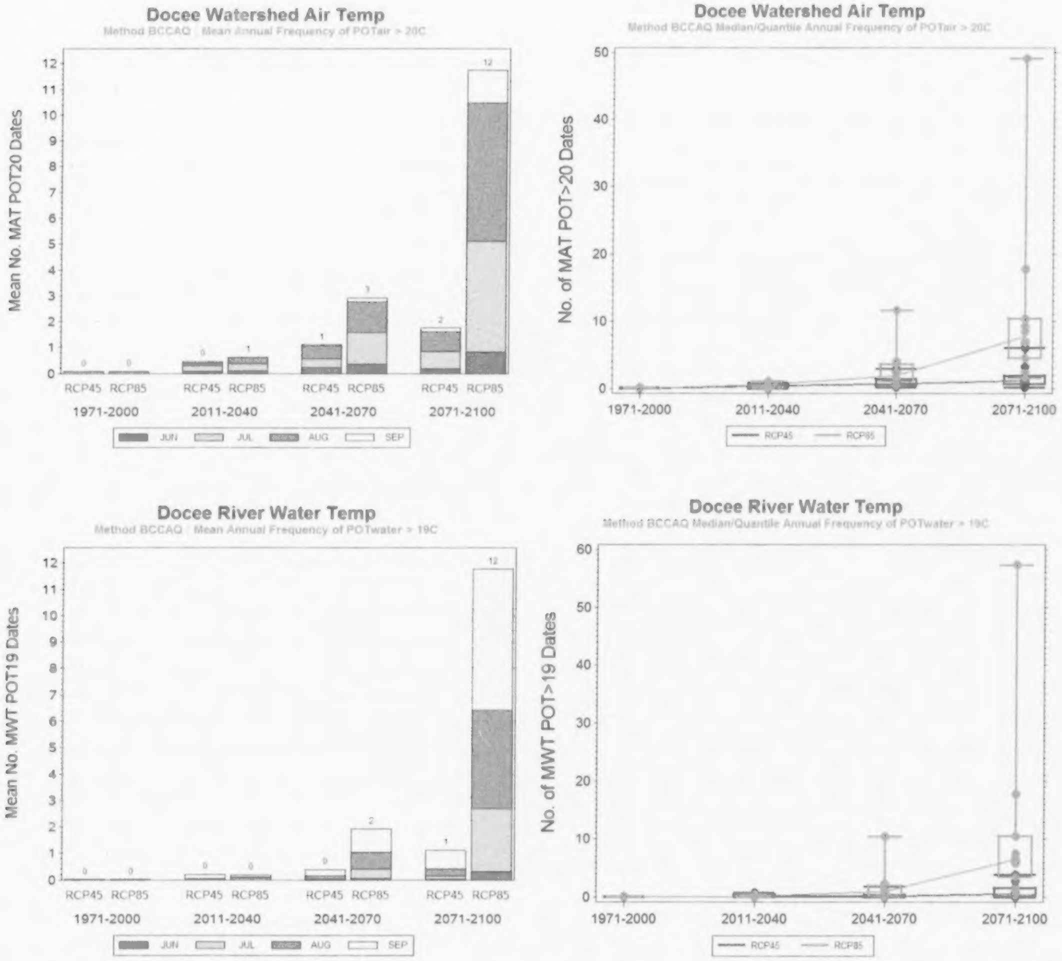


Figure 19. Projected POT events (mean number of dates exceeding threshold temperature) for regional air temperature (at Port Hardy; top), Docee water temperature (bottom). Bar charts indicate mean frequency of POT events by time-period, RCP scenario and month of year (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25^{th} & 75^{th} percentiles), and range (T-capped whiskers) statistics for frequency of POT events.

Docee Water Temperature – Projected POT$_{19°C}$ Dates By Month

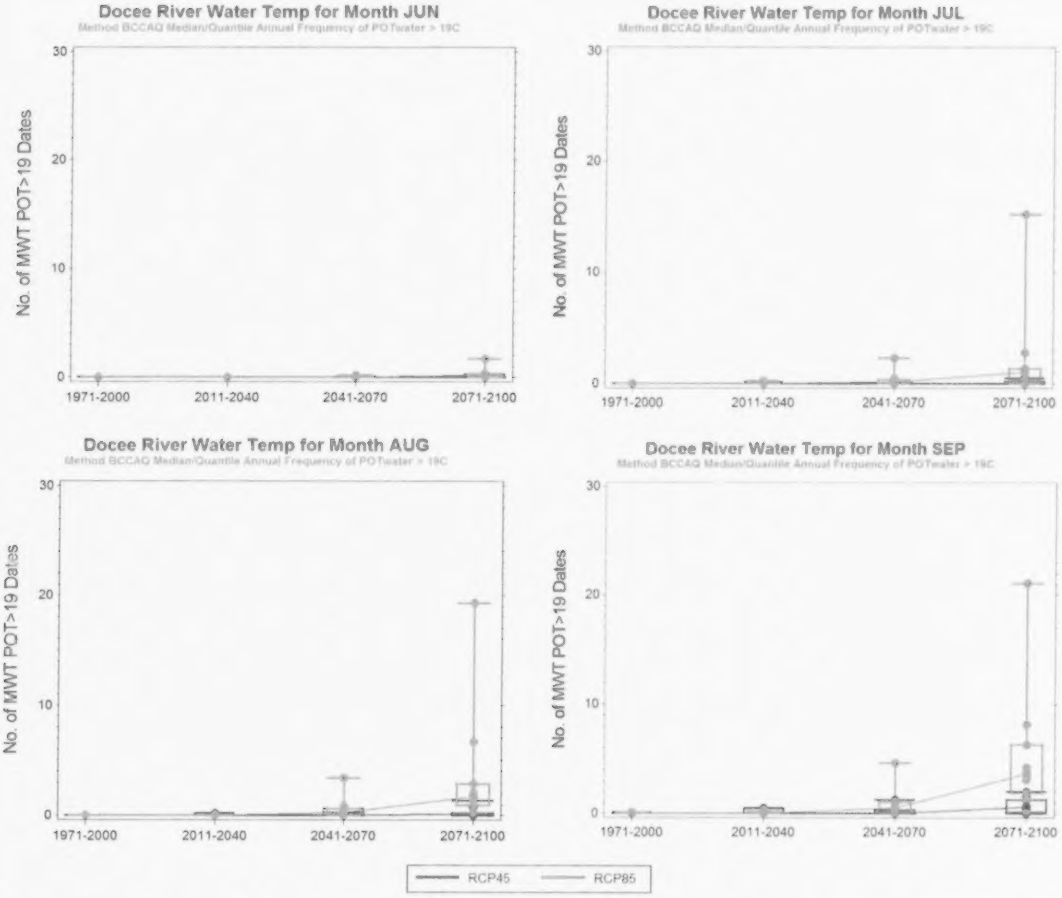


Figure 20. Mean annual frequency of POT temperature events for Docee River water temperature across all models and years by RCP, time-period, by month: June to September.

Docee Watershed Projected POT Event Duration by RCP

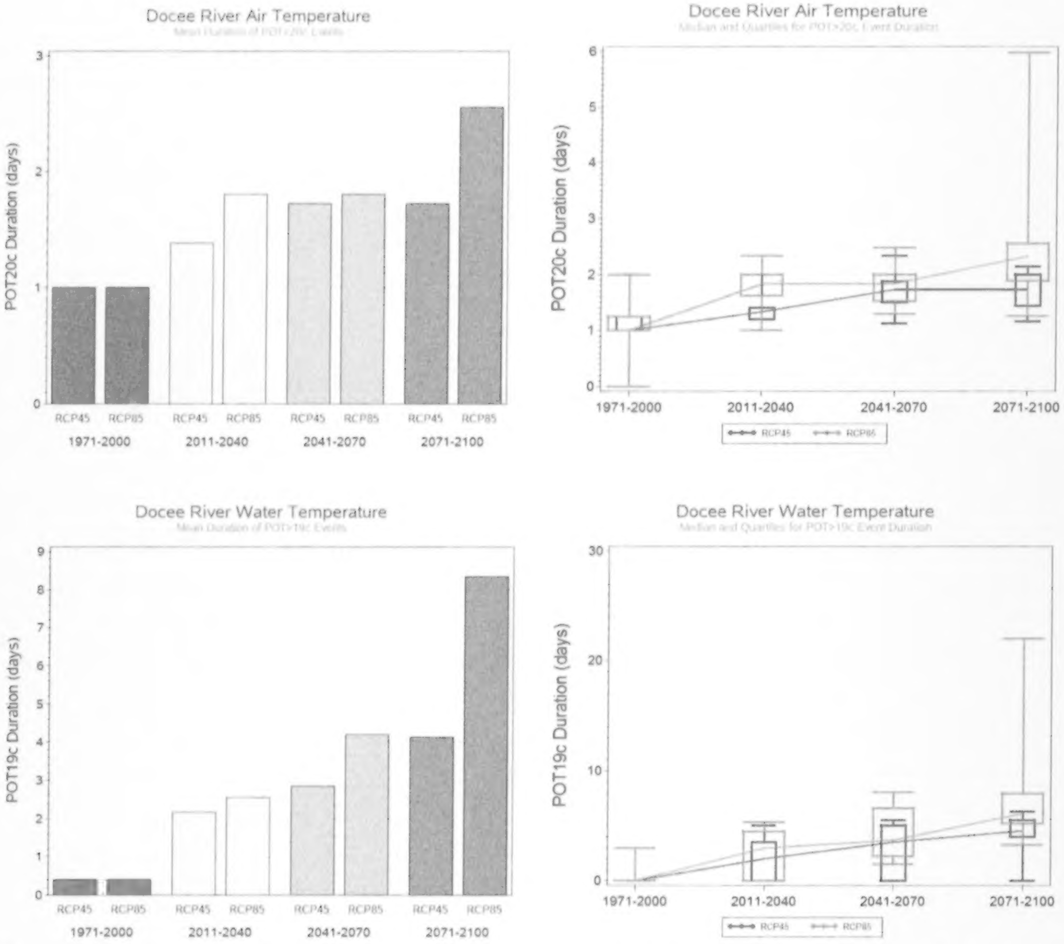


Figure 21. Projected POT continuous duration (mean number of continuous days exceeding threshold temperature) for regional air temperature (top), and Docee River water temperature (bottom). Bar charts indicate mean duration of POT events by time-period, RCP scenario (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for POT event duration.

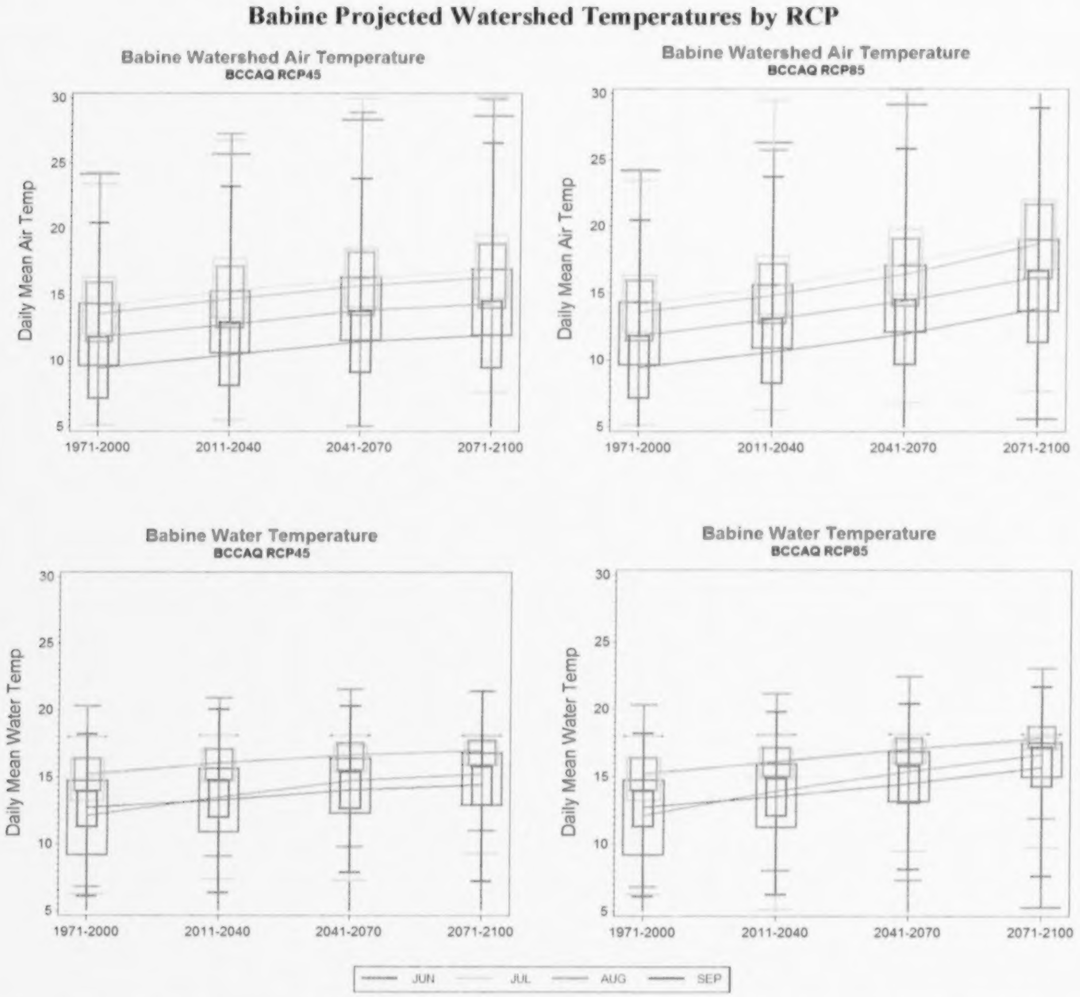


Figure 22. Trends in projected monthly regional watershed air temperature (median, quartiles and range) and Babine River water temperature, by month, across all BCCAQ GCM models and years within time-period (RCP 4.5, left; RCP 8.5, right).

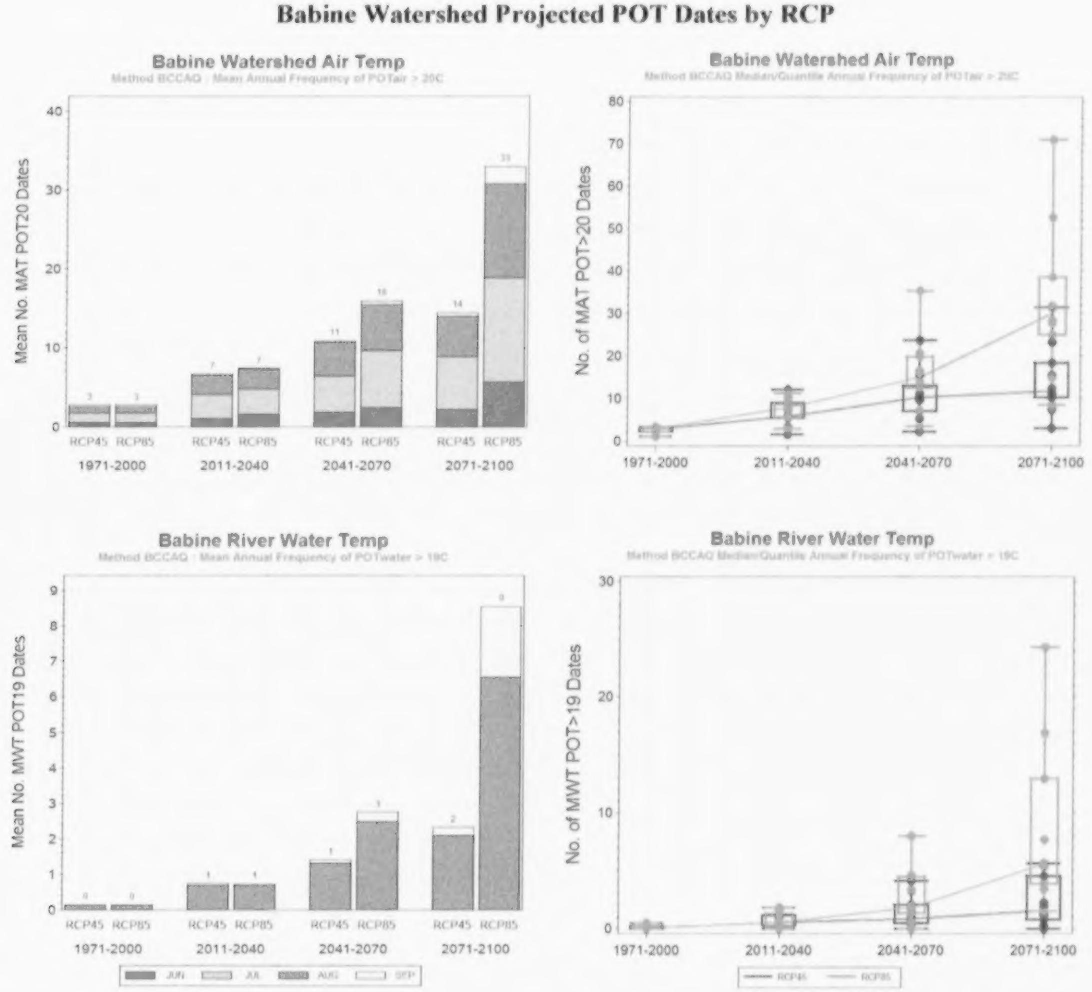


Figure 23. Projected POT events (mean number of dates exceeding threshold temperature) for regional air temperature (at Port Hardy; top), Docee water temperature (bottom). Bar charts indicate mean frequency of POT events by time-period, RCP scenario and month of year (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for frequency of POT events.

Babine Water Temperature – Projected $\text{POT}_{19°C}$ Dates By Month

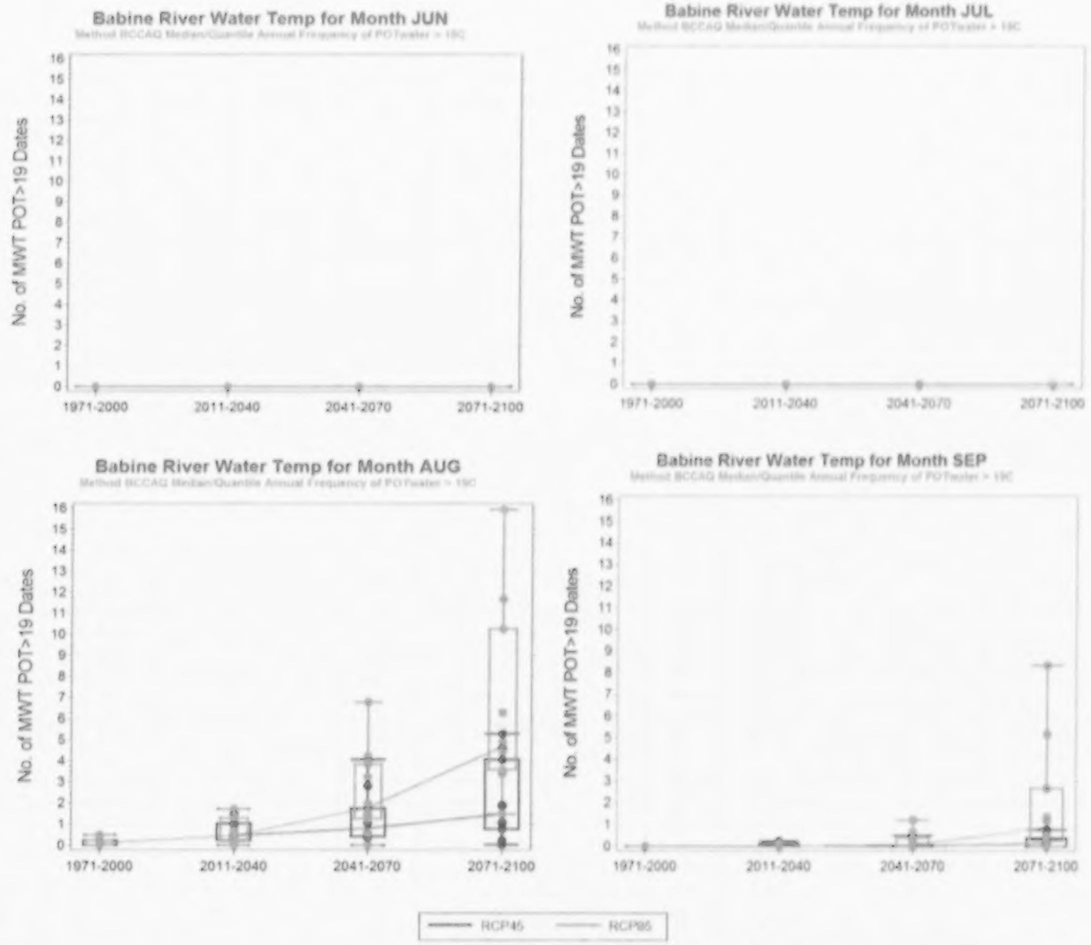


Figure 24. Mean annual frequency of POT temperature events for Babine River water temperature across all models and years by RCP, time-period, by month: June to September.

Babine Watershed Projected POT Event Duration by RCP

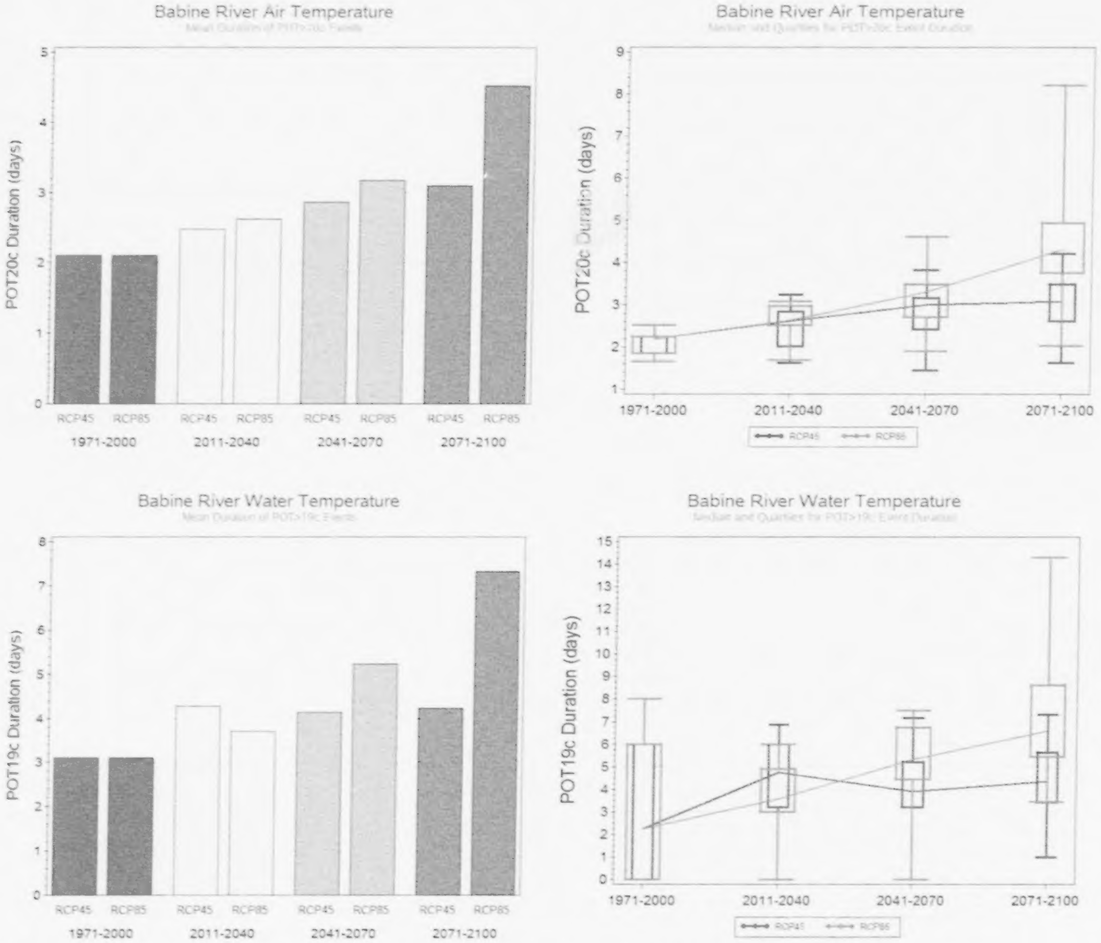
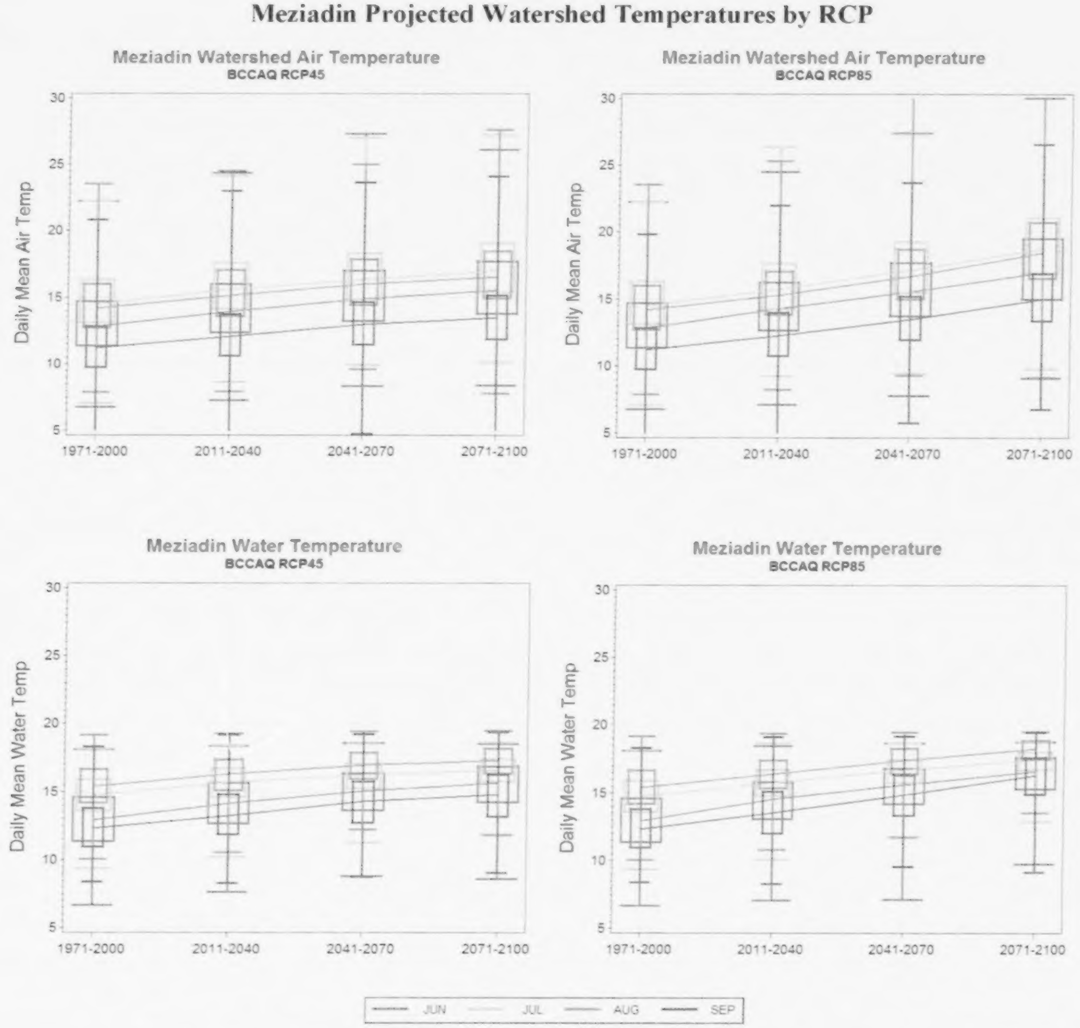


Figure 25. Projected POT continuous duration (mean number of continuous days exceeding threshold temperature) for regional air temperature (top), and Docee River water temperature (bottom). Bar charts indicate mean duration of POT events by time-period, RCP scenario (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for POT event duration.



Meziadin Projected Watershed Temperatures by RCP

Meziadin Watershed Air Temperature
BCCAQ RCP45

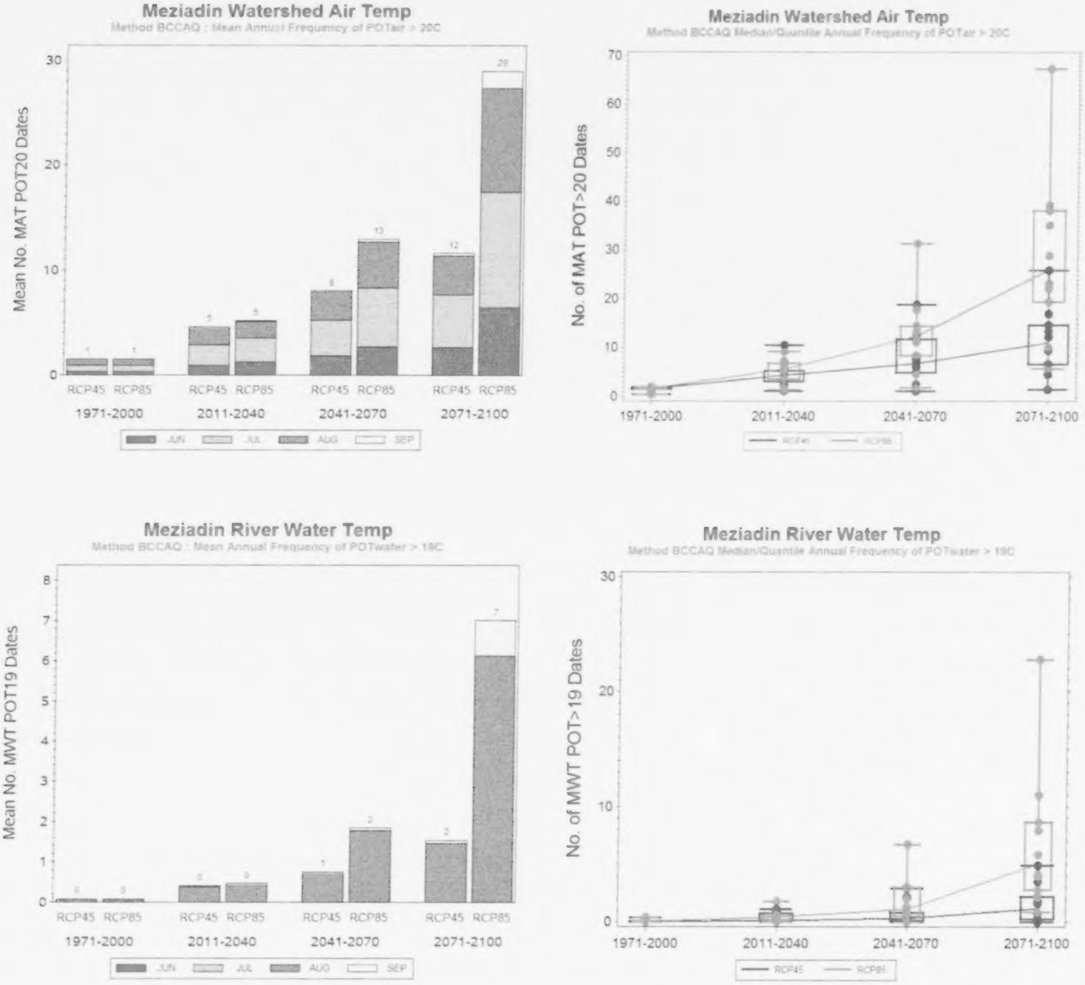
Meziadin Watershed Air Temperature
BCCAQ RCP85

Meziadin Water Temperature
BCCAQ RCP45

Meziadin Water Temperature
BCCAQ RCP85

Figure 26. Trends in projected monthly regional watershed air temperature (median, quartiles and range; top) and Meziadin River water temperature (bottom), by month, across all BCCAQ GCM models and years within time-period (RCP 4.5, left; RCP 8.5, right).

Meziadin Watershed Projected POT Dates by RCP


Meziadin Watershed Air Temp

Method BCCAQ : Mean Annual Frequency of POTair > 20C

Meziadin Watershed Air Temp

Method BCCAQ Median/Quantile Annual Frequency of POTair > 20C

Meziadin River Water Temp

Method BCCAQ : Mean Annual Frequency of POTwater > 19C

Meziadin River Water Temp

Method BCCAQ Median/Quantile Annual Frequency of POTwater > 19C

Figure 27. Projected POT events (mean number of dates exceeding threshold temperature) for regional air temperature (at Stewart; top), Meziadin water temperature (bottom). Bar charts indicate mean frequency of POT events by time-period, RCP scenario and month of year (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for frequency of POT events.

Meziadin Water Temperature – Projected POT$_{19°C}$ Dates By Month

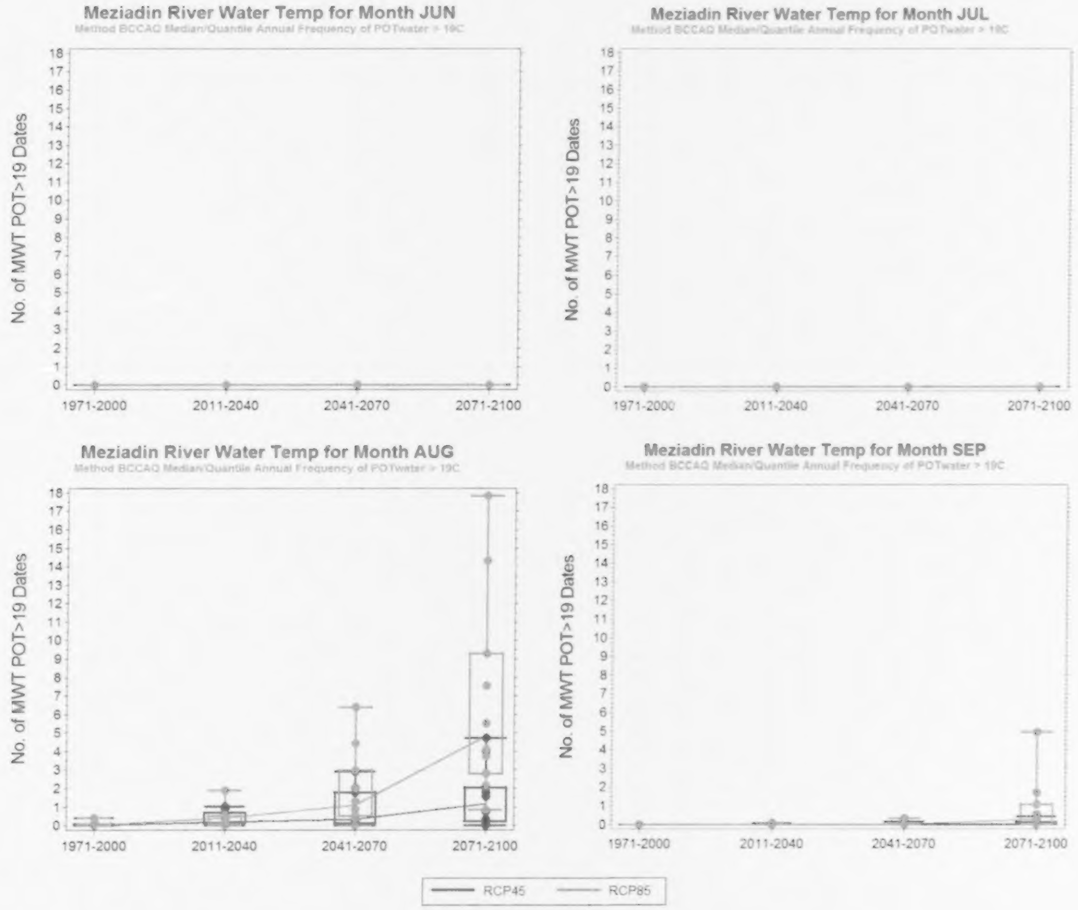


Figure 28. Mean annual frequency of POT temperature events for Meziadin River water temperature across all models and years by RCP, time-period, by month: June to September.

Meziadin Watershed Projected POT Event Duration by RCP

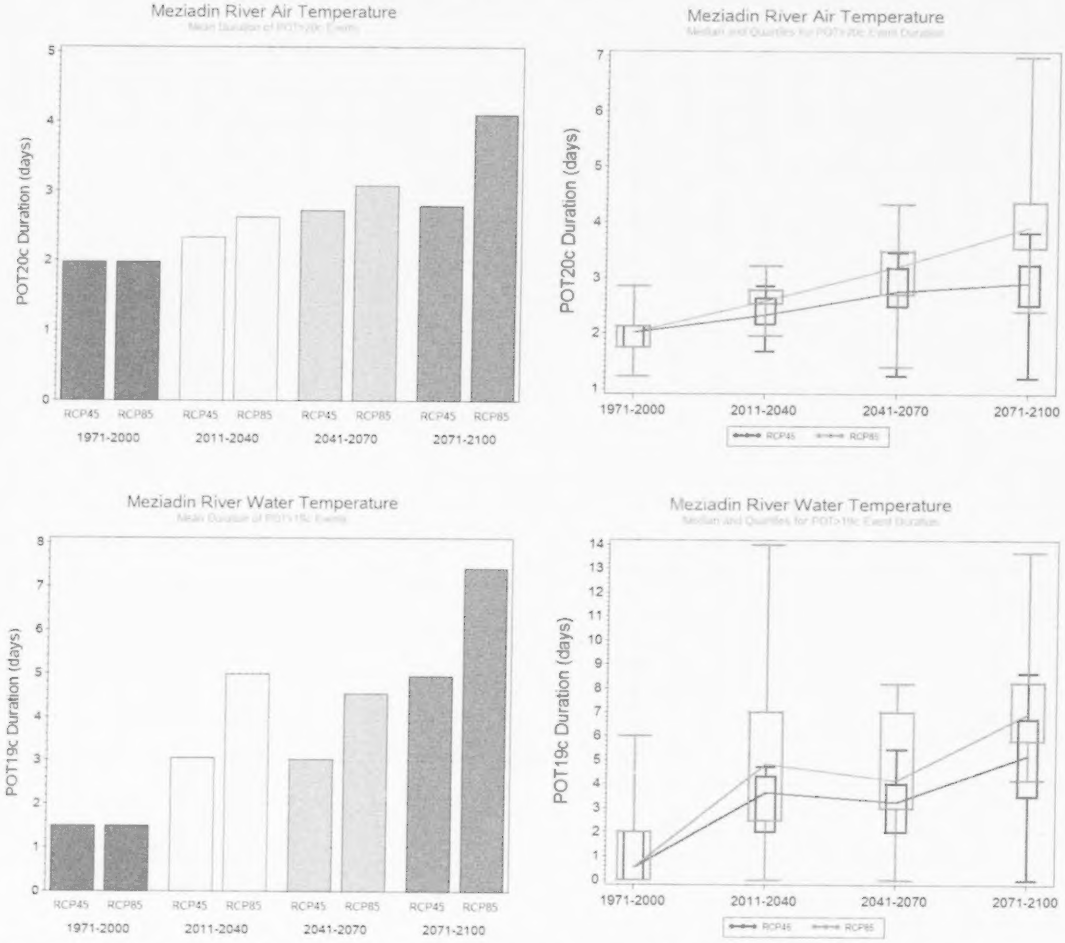


Figure 29. Projected POT continuous duration (mean number of continuous days exceeding threshold temperature) for regional air temperature (top), and Docee River water temperature (bottom). Bar charts indicate mean duration of POT events by time-period, RCP scenario (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for POT event duration.

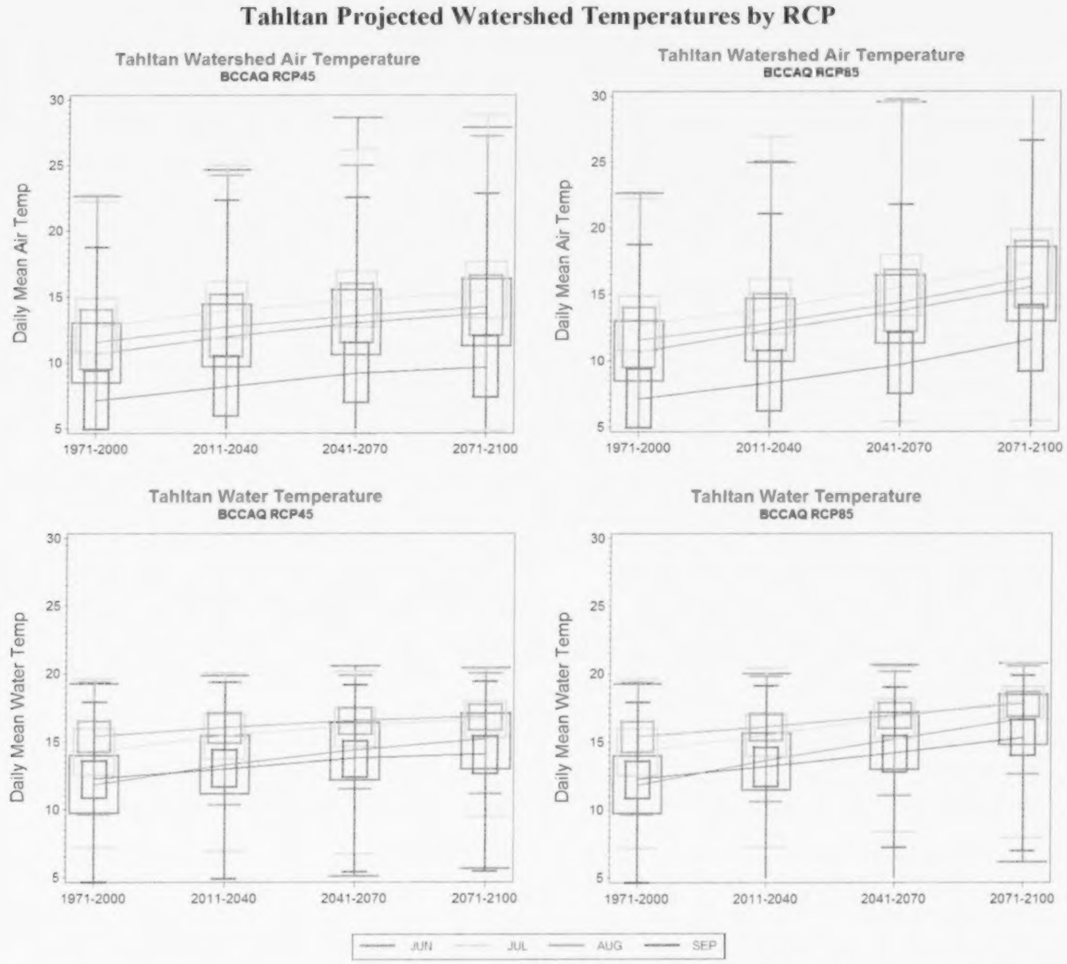


Figure 30. Trends in projected monthly regional watershed air temperature (median, quartiles and range) and Tahltan River water temperature, by month, across all BCCAQ GCM models and years within time-period (RCP 4.5, left; RCP 8.5, right).

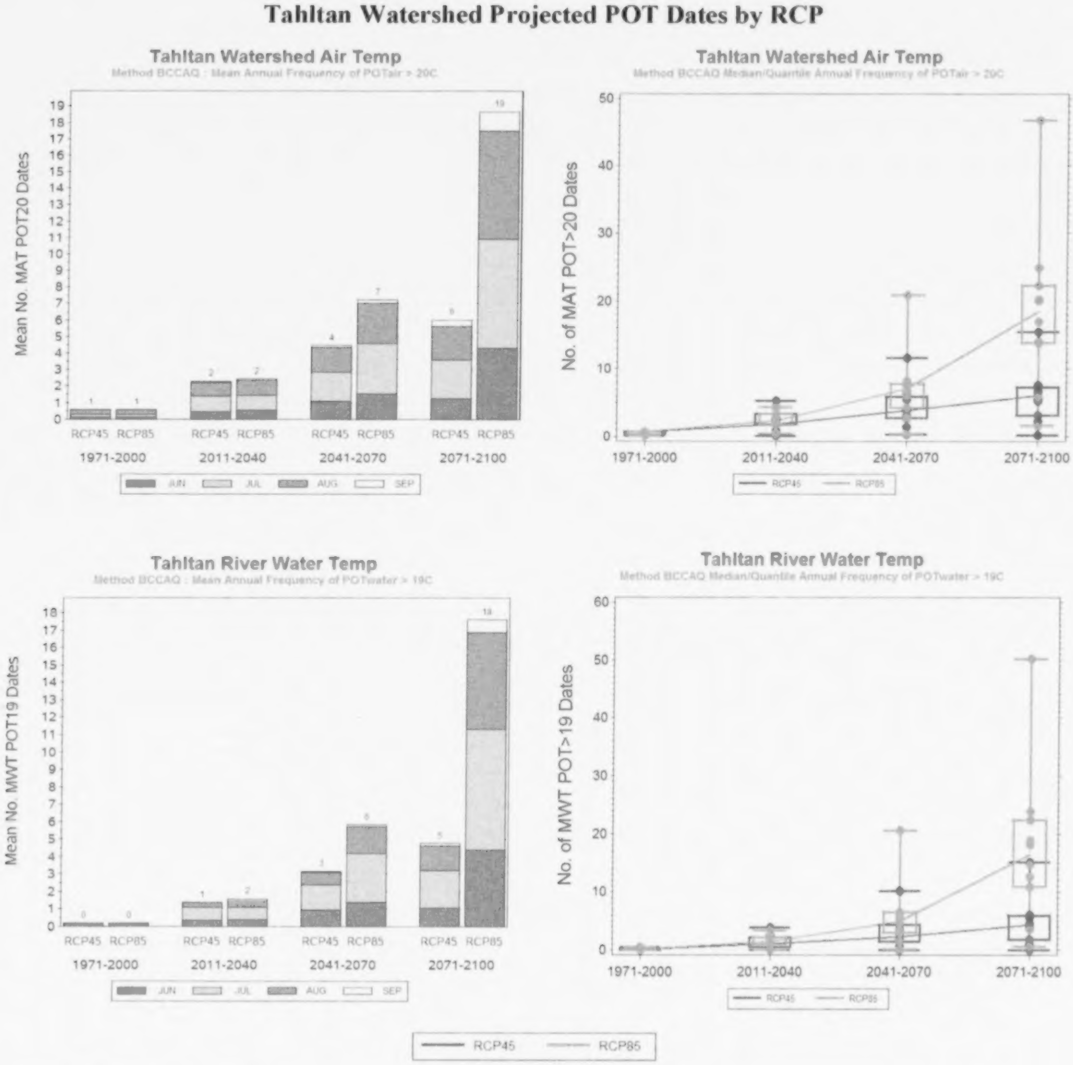


Figure 31. Projected POT events (mean number of dates exceeding threshold temperature) for regional air temperature (at Dease Lake; top), Tahltan water temperature (bottom). Bar charts indicate mean frequency of POT events by time-period, RCP scenario and month of year (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for frequency of POT events.

Tahltan Water Temperature – Projected POT$_{19°C}$ Dates By Month

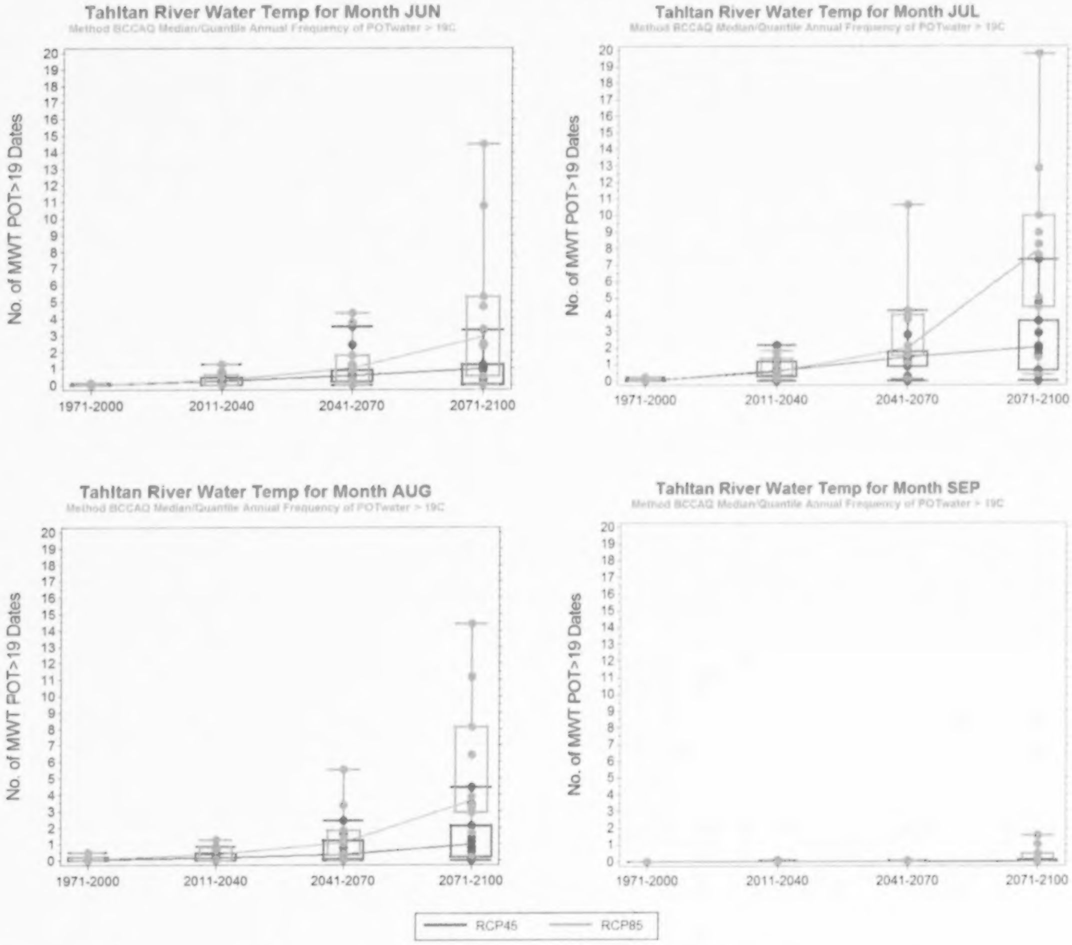
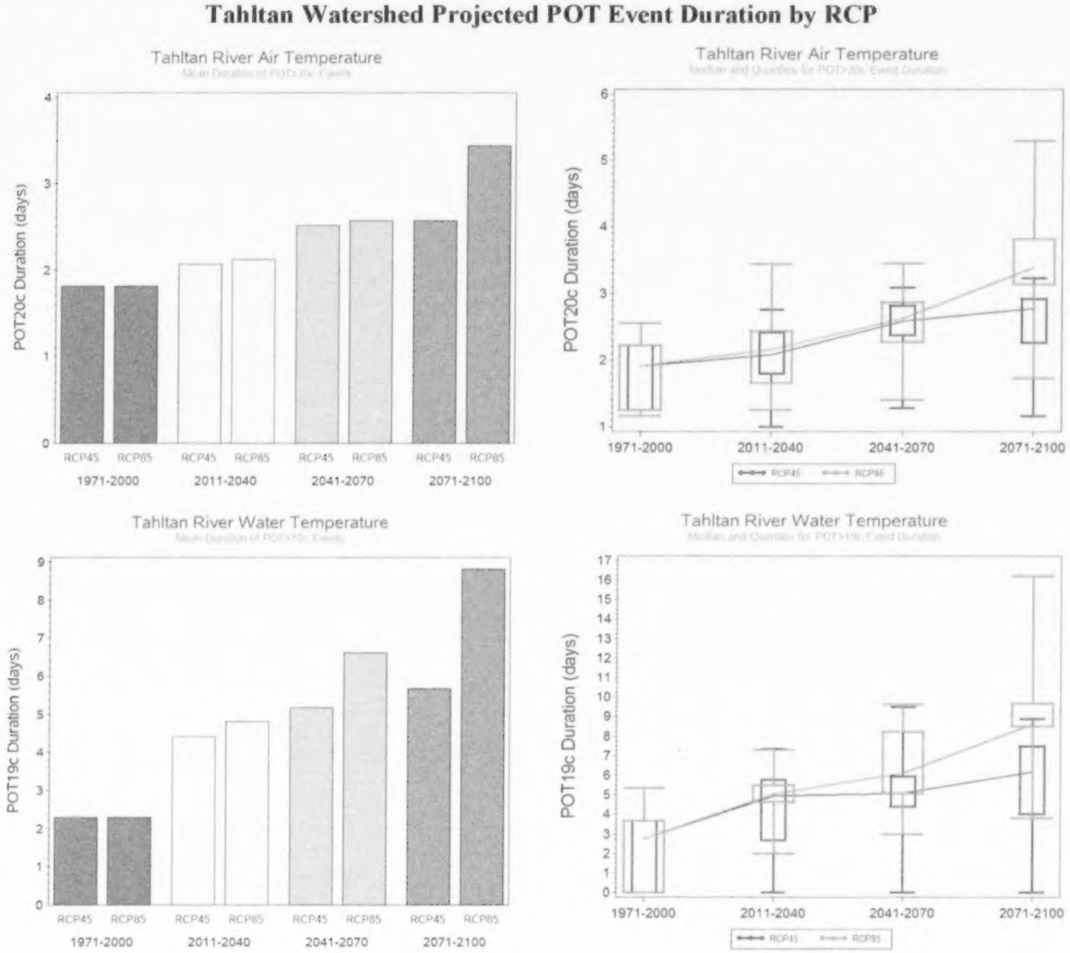


Figure 32. Mean annual frequency of POT temperature events for Tahltan River water temperature across all models and years by RCP, time-period, by month: June to September.



Tahltan Watershed Projected POT Event Duration by RCP

Figure 33. Projected POT continuous duration (mean number of continuous days exceeding threshold temperature) for regional air temperature (Dease Lake, top), and Tahltan River water temperature (bottom). Bar charts indicate mean duration of POT events by time-period, RCP scenario (June-September) for 10 GCM models. Box plots indicate median (connected by solid line), quartile (box delineates 25th & 75th percentiles), and range (T-capped whiskers) statistics for POT event duration.

TABLES

Watershed Properties

River	Lat x Long (degrees)	Mean Annual Discharge (m^3/s)	Gross Drainage Area (km^2)	River Length (km)	Headwater Lake Area (km^2)	Lake Mean/Max[52] Depth (m)	Elev[53] (m)
Babine	55.32x126.63	~270[54]	6,760	98	461	61/186	711
Docee	51.25x127.15	N/A	408	<1	21	80/170	15
Meziadin	56.04x129.20	N/A	530	6	37	/135	244
Somass	49.28x124.87	121	1,280	10/30[55]	-	/250[56]	5-10[57]
Sproat	49.28x124.91	38	351	2	52	/185	29
Tahltan	57.95x131.62	N/A	N/A	55	5	23/48	812

Table 1. Watershed properties.

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[52] Assumed maximum depth, if only one number provided.

[53] Elevation corresponds to headwater lake altitude, unless otherwise specified.

[54] Levy and Hall (1985).

[55] Somass River – consists of 6.5 km tidewater and 3.5 km freshwater to Sproat River confluence. Stamp River, draining Great Central Lake, is another 20 km in length.

[56] Refers to Great Central Lake only, which drains into Stamp River then Somass River.

[57] Somass River elevation corresponding to lower 10 km, from Sproat River confluence to Somass River mouth.

Somass Watershed – Projected Monthly Temperature Statistics

Site: Somass
and Method: BCCAQ

		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	15.5	3.1	18.2	3.0	18.2	2.9	15.3	2.9	16.6	2.1	18.8	1.6	19.6	1.2	17.8	1.5
	2011-2040	16.3	3.2	19.4	3.1	19.4	2.9	16.4	3.0	17.3	2.0	19.6	1.5	20.2	1.1	18.5	1.5
	2041-2070	17.3	3.3	20.3	3.1	20.5	3.0	17.3	3.0	18.0	1.9	20.1	1.3	20.7	1.1	19.0	1.4
	2071-2100	17.7	3.2	21.0	3.3	21.0	3.0	17.8	3.1	18.4	1.8	20.4	1.3	20.9	1.0	19.3	1.4
RCP85	1971-2000	15.5	3.1	18.2	3.0	18.2	2.9	15.3	2.9	16.6	2.1	18.8	1.6	19.6	1.2	17.8	1.5
	2011-2040	16.6	3.2	19.6	3.1	19.6	2.9	16.6	3.1	17.5	2.0	19.7	1.4	20.3	1.1	18.6	1.5
	2041-2070	17.8	3.3	21.3	3.3	21.1	3.2	17.9	3.1	18.5	1.9	20.5	1.3	21.0	1.1	19.3	1.4
	2071-2100	19.4	3.5	23.0	3.4	23.3	3.3	19.8	3.4	19.4	1.6	21.3	1.0	21.8	0.9	20.3	1.4

Site: Somass
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	13	15	17	16	18	20	16	18	20	13	15	17	15	17	18	18	19	20	19	20	20	17	18	19
	2011-2040	14	16	18	17	19	21	17	19	21	14	16	18	16	17	19	19	20	21	19	20	21	18	18	19
	2041-2070	15	17	19	18	20	22	18	20	23	15	17	19	17	18	19	19	20	21	20	21	21	18	19	20
	2071-2100	15	17	20	19	21	23	19	21	23	16	18	20	17	19	20	20	21	21	20	21	22	18	19	20
RCP85	1971-2000	13	15	17	16	18	20	16	18	20	13	15	17	15	17	18	18	19	20	19	20	20	17	18	19
	2011-2040	14	16	19	17	19	22	17	19	21	14	16	19	16	18	19	19	20	21	20	20	21	18	19	20
	2041-2070	15	17	20	19	21	23	19	21	23	16	18	20	17	19	20	20	21	21	20	21	22	18	19	20
	2071-2100	17	19	21	21	23	25	21	23	25	17	20	22	18	20	21	21	21	22	21	22	22	19	20	21

Table 2. Somass watershed projected air temperature and lower Somass water temperature (°C) quartile statistics (25th, 50th, and 75th percentiles), across all GCM models by RCP, time-period and month.

Sproat Watershed – Projected Monthly Temperature Statistics

Site: Sproat
and Method: BCCAQ

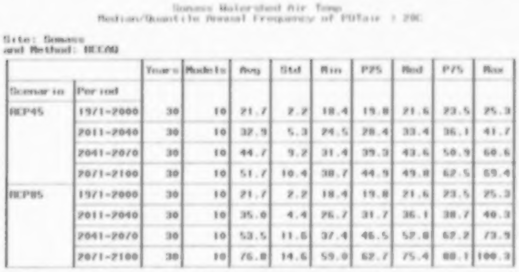
		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	15.5	3.1	18.2	3.0	18.2	2.9	15.3	2.9	17.9	2.1	20.1	1.6	21.6	1.2	19.7	1.6
	2011-2040	16.3	3.2	19.4	3.1	19.4	2.9	16.4	3.0	18.6	2.0	20.8	1.4	22.2	1.1	20.4	1.5
	2041-2070	17.3	3.3	20.3	3.1	20.5	3.0	17.3	3.0	19.4	1.8	21.3	1.2	22.7	1.0	20.9	1.5
	2071-2100	17.7	3.2	21.0	3.3	21.0	3.0	17.8	3.1	19.7	1.7	21.6	1.2	22.9	1.0	21.3	1.5
RCP85	1971-2000	15.5	3.1	18.2	3.0	18.2	2.9	15.3	2.9	17.9	2.1	20.1	1.6	21.6	1.2	19.7	1.6
	2011-2040	16.6	3.2	19.6	3.1	19.6	2.9	16.6	3.1	18.9	1.9	21.0	1.3	22.2	1.1	20.5	1.5
	2041-2070	17.8	3.3	21.3	3.3	21.1	3.2	17.9	3.1	19.7	1.8	21.7	1.2	22.9	1.0	21.3	1.4
	2071-2100	19.4	3.5	23.0	3.4	23.3	3.3	19.8	3.4	20.7	1.5	22.4	1.0	23.7	0.8	22.3	1.4

Site: Sproat
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	13	15	17	16	18	20	16	18	20	13	15	17	17	18	19	19	20	21	21	22	22	19	20	21
	2011-2040	14	16	18	17	19	21	17	19	21	14	16	18	17	19	20	20	21	22	21	22	23	19	20	21
	2041-2070	15	17	19	18	20	22	18	20	23	15	17	19	18	19	21	21	21	22	22	23	23	20	21	22
	2071-2100	15	17	20	19	21	23	19	21	23	16	18	20	19	20	21	21	22	22	22	23	24	20	21	22
RCP85	1971-2000	13	15	17	16	18	20	16	18	20	13	15	17	17	18	19	19	20	21	21	22	22	19	20	21
	2011-2040	14	16	19	17	19	22	17	19	21	14	16	19	18	19	20	20	21	22	22	22	23	19	21	22
	2041-2070	15	17	20	19	21	23	19	21	23	16	18	20	19	20	21	21	22	23	22	23	24	20	21	22
	2071-2100	17	19	21	21	23	25	21	23	25	17	20	22	20	21	22	22	22	23	23	24	24	21	22	23

Table 3. Somass watershed projected air temperature and Sproat River water temperature (°C) quartile statistics (25th, 50th, and 75th percentiles), across all GCM models by RCP, time-period and month.

Somass / Sproat Watershed - POT Frequency Tables



Somass Watershed Air Temp
Median/Quantile Annual Frequency of POTair > 20C

Site: Somass
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	21.7	2.2	18.4	19.8	21.6	23.5	25.3
	2011-2040	30	10	32.9	5.3	24.5	28.4	33.4	36.1	41.7
	2041-2070	30	10	44.7	9.2	31.4	39.3	43.6	50.9	60.6
	2071-2100	30	10	51.7	10.4	38.7	44.9	49.8	62.5	69.4
RCP85	1971-2000	30	10	21.7	2.2	18.4	19.8	21.6	23.5	25.3
	2011-2040	30	10	35.0	4.4	26.7	31.7	36.1	38.7	40.3
	2041-2070	30	10	53.5	11.6	37.4	46.5	52.8	62.2	73.9
	2071-2100	30	10	76.8	14.6	59.0	62.7	75.4	88.1	100.3

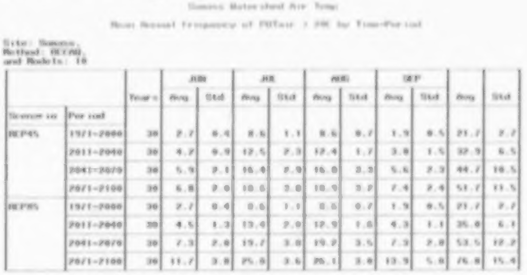
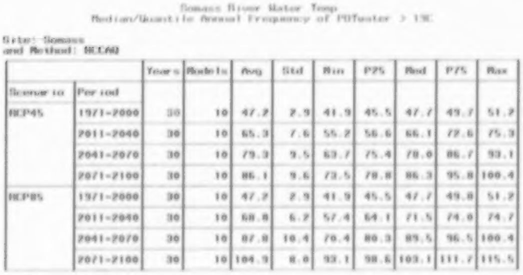


Table 4. Somass Air Temperature. Mean annual frequency of POT20 °C air temperature events across all models and years by RCP, time-period (left), and by month (right).



Somass River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Somass
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	47.2	2.9	41.9	45.5	47.7	49.7	51.2
	2011-2040	30	10	65.3	7.6	55.2	56.6	66.1	72.6	75.3
	2041-2070	30	10	79.3	9.5	63.7	75.4	78.0	86.7	93.1
	2071-2100	30	10	86.1	9.6	73.5	78.8	86.3	95.8	100.4
RCP85	1971-2000	30	10	47.2	2.9	41.9	45.5	47.7	49.8	51.2
	2011-2040	30	10	68.8	6.2	57.4	64.1	71.5	74.0	74.7
	2041-2070	30	10	87.8	10.4	70.4	80.3	89.5	96.5	100.4
	2071-2100	30	10	104.9	8.0	93.1	98.6	103.1	111.7	115.5

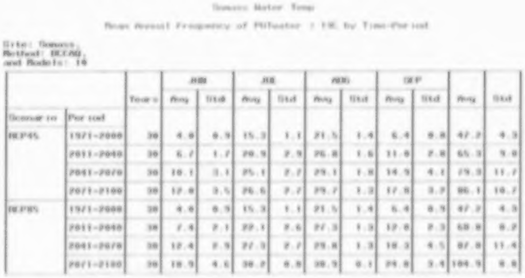
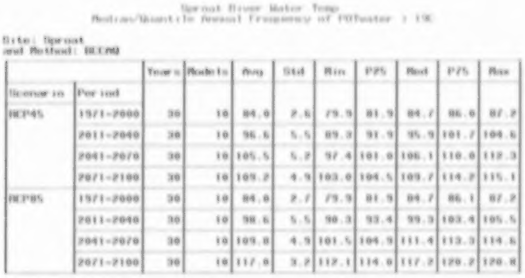


Table 5. Somass Water Temperature. Mean annual frequency of POT19 °C water temperature events across all models and years by RCP, time-period (left), and by month (right).



Sproat River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Sproat
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	84.0	2.6	79.9	81.9	84.7	86.0	87.2
	2011-2040	30	10	96.6	5.5	89.3	91.9	95.9	101.7	104.6
	2041-2070	30	10	105.5	5.2	97.4	101.0	106.1	110.0	112.3
	2071-2100	30	10	109.2	4.9	103.0	104.5	109.7	114.2	115.1
RCP85	1971-2000	30	10	84.0	2.7	79.9	81.9	84.7	86.1	87.2
	2011-2040	30	10	98.6	5.5	90.3	93.4	99.3	103.4	105.5
	2041-2070	30	10	109.8	4.9	101.5	104.9	111.4	113.3	114.6
	2071-2100	30	10	117.0	3.2	112.1	114.0	117.2	120.2	120.8

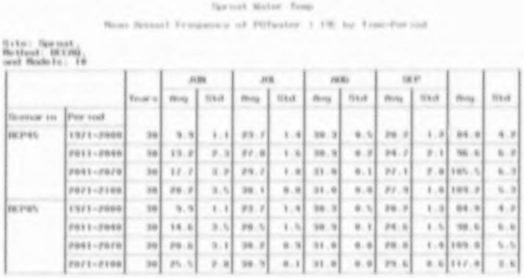


Table 6. Sproat Water Temperature. Mean annual frequency of POT19 °C water temperature events across all models and years by RCP, time-period (left), and by month (right).

Somass / Sproat Watershed - POT Duration Tables

Somass River Air Temperature
Median and Quartiles for POT:20c Event Duration

Site Somass
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	3.0	0.3	2.4	2.8	3.0	3.1	3.6
	2011-2040	10	3.6	0.5	2.9	3.3	3.6	3.7	4.4
	2041-2070	10	4.3	0.8	3.3	3.8	4.3	4.7	6.0
	2071-2100	10	5.0	1.2	3.8	4.1	4.5	6.2	7.4
RCP85	1971-2000	10	3.0	0.3	2.4	2.8	3.0	3.1	3.6
	2011-2040	10	3.7	0.5	3.2	3.2	3.6	4.2	4.5
	2041-2070	10	5.2	1.6	3.6	4.3	4.9	5.6	9.2
	2071-2100	10	8.9	4.3	5.2	5.5	7.6	10.0	18.5
All		80	4.6	2.5	2.4	3.2	3.8	4.9	18.5

Table 7. Somass Air Temperature. Mean annual duration of continuous POT20 °C air temperature events across all models and years by time-period and month.

Somass River Water Temperature
Median and Quartiles for POT:19c Event Duration

Site Somass
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	13.4	1.6	11.1	12.3	13.1	14.3	16.9
	2011-2040	10	19.5	4.0	14.5	16.2	19.2	21.1	27.6
	2041-2070	10	27.0	7.4	14.7	22.9	26.9	31.0	41.1
	2071-2100	10	32.0	10.6	19.8	25.1	29.0	37.3	54.7
RCP85	1971-2000	10	13.4	1.6	11.1	12.3	13.1	14.3	16.9
	2011-2040	10	20.2	2.8	16.1	18.6	20.1	22.4	24.7
	2041-2070	10	33.2	9.5	19.9	26.3	32.3	38.1	51.9
	2071-2100	10	54.7	14.7	35.0	39.3	56.2	63.2	78.7
All		80	26.7	14.9	11.1	14.9	22.6	32.6	78.7

Table 8. Somass Water Temperature. Mean annual duration of continuous POT19 °C water temperature events across all models and years by time-period and month.

Sproat River Water Temperature
Median and Quartiles for POT:19c Event Duration

Site Sproat
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	26.9	2.9	22.4	25.3	26.8	28.7	31.0
	2011-2040	10	40.6	8.3	31.2	35.1	37.7	43.0	58.7
	2041-2070	10	51.2	7.4	40.0	46.1	52.1	53.8	66.1
	2071-2100	10	58.0	13.0	42.5	48.1	55.7	66.4	84.2
RCP85	1971-2000	10	26.9	2.8	22.4	25.3	26.8	28.7	31.0
	2011-2040	10	41.3	5.1	35.7	36.9	40.8	44.7	50.3
	2041-2070	10	56.3	10.6	39.8	49.9	56.4	62.9	71.6
	2071-2100	10	83.3	16.2	62.2	71.2	80.3	100.1	109.8
All		80	48.0	19.7	22.4	31.1	44.5	58.4	109.8

Table 9. Sproat Water Temperature. Mean annual duration of continuous POT19 °C water temperature events across all models and years by time-period and month.

Docee Watershed – Projected Monthly Temperature Statistics

Site: Docee
and Method: BCCAQ

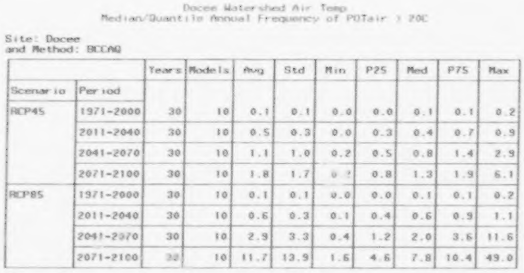
		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	12.0	1.8	13.8	1.6	14.1	1.6	12.3	1.8	11.3	1.6	13.3	1.4	13.8	1.4	15.2	1.4
	2011-2040	12.8	1.9	14.8	1.7	15.1	1.6	13.2	1.9	12.1	1.7	14.3	1.4	14.8	1.4	16.0	1.3
	2041-2070	13.6	2.0	15.6	1.7	15.9	1.7	14.0	1.9	12.9	1.7	15.1	1.3	15.6	1.4	16.6	1.2
	2071-2100	14.0	1.9	16.2	1.8	16.4	1.7	14.4	1.9	13.4	1.7	15.7	1.4	16.1	1.3	17.0	1.2
RCP85	1971-2000	12.0	1.8	13.8	1.6	14.1	1.6	12.3	1.8	11.3	1.6	13.3	1.4	13.8	1.4	15.2	1.4
	2011-2040	13.0	2.0	15.0	1.7	15.2	1.6	13.4	1.9	12.4	1.8	14.5	1.4	14.9	1.4	16.1	1.3
	2041-2070	14.1	2.0	16.4	1.9	16.5	1.9	14.5	2.0	13.5	1.8	15.8	1.5	16.1	1.4	17.1	1.2
	2071-2100	15.4	2.1	17.9	2.0	18.2	2.0	16.1	2.2	14.9	1.8	17.1	1.3	17.5	1.2	18.0	1.0

Site: Docee
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	11	12	13	13	14	15	13	14	15	11	12	13	10	11	12	12	13	14	13	14	15	14	15	16
	2011-2040	11	13	14	14	15	16	14	15	16	12	13	14	11	12	13	13	14	15	14	15	16	15	16	17
	2041-2070	12	13	15	14	16	17	15	16	17	13	14	15	12	13	14	14	15	16	15	16	17	16	17	18
	2071-2100	13	14	15	15	16	17	15	16	17	13	14	16	12	13	15	15	16	17	15	16	17	16	17	18
RCP85	1971-2000	11	12	13	13	14	15	13	14	15	11	12	13	10	11	12	12	13	14	13	14	15	14	15	16
	2011-2040	12	13	14	14	15	16	14	15	16	12	13	15	11	12	13	14	14	15	14	15	16	15	16	17
	2041-2070	13	14	15	15	16	18	15	16	18	13	14	16	12	13	15	15	16	17	15	16	17	16	17	18
	2071-2100	14	15	17	16	18	19	17	18	19	15	16	18	14	15	16	16	17	18	17	18	18	17	18	19

Table 10. Projected mean regional air (Port Hardy) and Docee River water temperature (°C) statistics (mean, standard deviation; top) and quartiles (25th, 50th, and 75th percentiles; bottom), across all GCM models by RCP, time-period and month.

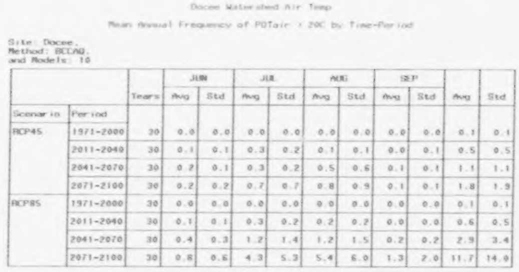
Docee Watershed - POT Frequency Tables



Docee Watershed Air Temp
Median/Quantile Annual Frequency of POTair > 20C

Site: Docee
and Method: BCCAQ

		Years	Models	Avg	Std	Min	P25	Med	P75	Max
Scenario	Period									
RCP45	1971-2000	30	10	0.1	0.1	0.0	0.0	0.1	0.1	0.2
	2011-2040	30	10	0.5	0.3	0.0	0.3	0.4	0.7	0.9
	2041-2070	30	10	1.1	1.0	0.2	0.5	0.8	1.4	2.9
	2071-2100	30	10	1.8	1.7	[illegible]	0.8	1.3	1.9	6.1
RCP85	1971-2000	30	10	0.1	0.1	0.0	0.0	0.1	0.1	0.2
	2011-2040	30	10	0.6	0.3	0.1	0.4	0.6	0.9	1.1
	2041-2070	30	10	2.9	3.3	0.4	1.2	2.0	3.6	11.6
	2071-2100	30	10	11.7	13.9	1.6	4.6	7.8	10.4	49.0

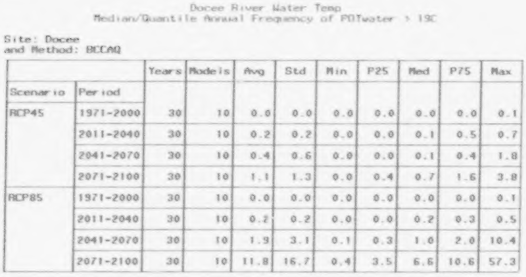


Docee Watershed Air Temp
Mean Annual Frequency of POTair > 20C by Time-Period

Site: Docee,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	2011-2040	30	0.1	0.1	0.3	0.2	0.1	0.1	0.0	0.1	0.5	0.5
	2041-2070	30	0.2	0.1	0.3	0.2	0.5	0.6	0.1	0.1	1.1	1.1
	2071-2100	30	0.2	0.2	0.7	0.7	0.8	0.9	0.1	0.1	1.8	1.9
RCP85	1971-2000	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	2011-2040	30	0.1	0.1	0.3	0.2	0.2	0.2	0.0	0.0	0.6	0.5
	2041-2070	30	0.4	0.3	1.2	1.4	1.2	1.5	0.2	0.2	2.9	3.4
	2071-2100	30	0.8	0.6	4.3	5.3	5.4	6.0	1.3	2.0	11.7	14.0

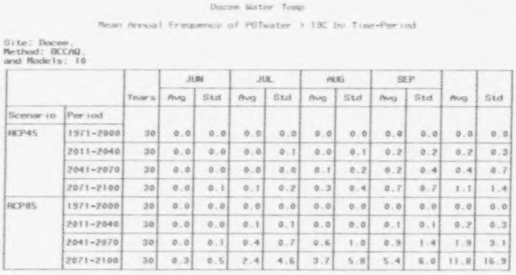
Table 11. Regional Air Temperature (Port Hardy). Mean annual frequency of $\mathrm{POT}_{20\ ^{\circ}C}$ air temperature events across all models and years by RCP, time-period and month.



Docee River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Docee
and Method: BCCAQ

		Years	Models	Avg	Std	Min	P25	Med	P75	Max
Scenario	Period									
RCP45	1971-2000	30	10	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	2011-2040	30	10	0.2	0.2	0.0	0.0	0.1	0.5	0.7
	2041-2070	30	10	0.4	0.6	0.0	0.0	0.1	0.4	1.8
	2071-2100	30	10	1.1	1.3	0.0	0.4	0.7	1.6	3.8
RCP85	1971-2000	30	10	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	2011-2040	30	10	0.2	0.2	0.0	0.0	0.2	0.3	0.5
	2041-2070	30	10	1.9	3.1	0.1	0.3	1.0	2.0	10.4
	2071-2100	30	10	11.8	16.7	0.4	3.5	6.6	10.6	57.3



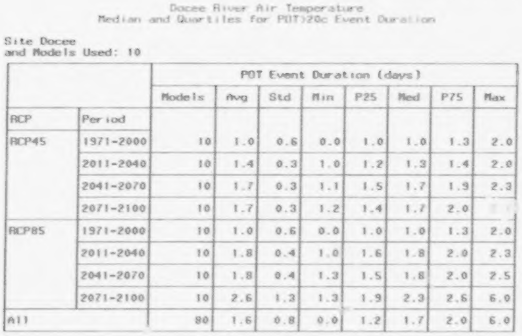
Docee Water Temp
Mean Annual Frequency of POTwater > 19C by Time-Period

Site: Docee,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2011-2040	30	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2	0.2	0.3
	2041-2070	30	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.4	0.4	0.7
	2071-2100	30	0.0	0.1	0.1	0.2	0.3	0.4	0.7	0.7	1.1	1.4
RCP85	1971-2000	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2011-2040	30	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.2	0.3
	2041-2070	30	0.0	0.1	0.4	0.7	0.6	1.0	0.9	1.4	1.9	3.1
	2071-2100	30	0.3	0.5	2.4	4.6	3.7	5.8	5.4	6.0	11.8	16.9

Table 12. Docee River (Long Lake) Water Temperature. Mean annual frequency of $\mathrm{POT}_{19\ ^{\circ}C}$ water temperature events across all models and years by RCP, time-period and month.

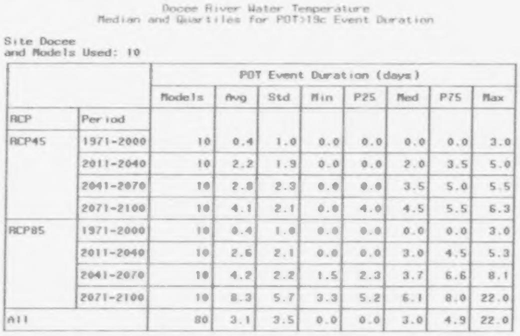
Docee Watershed - POT Duration Tables



Docee River Air Temperature
Median and Quartiles for POT>20c Event Duration

Site Docee
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	1.0	0.6	0.0	1.0	1.0	1.3	2.0
	2011-2040	10	1.4	0.3	1.0	1.2	1.3	1.4	2.0
	2041-2070	10	1.7	0.3	1.1	1.5	1.7	1.9	2.3
	2071-2100	10	1.7	0.3	1.2	1.4	1.7	2.0	[illegible]
RCP85	1971-2000	10	1.0	0.6	0.0	1.0	1.0	1.3	2.0
	2011-2040	10	1.8	0.4	1.0	1.6	1.8	2.0	2.3
	2041-2070	10	1.8	0.4	1.3	1.5	1.8	2.0	2.5
	2071-2100	10	2.6	1.3	1.3	1.9	2.3	2.6	6.0
All		80	1.6	0.8	0.0	1.2	1.7	2.0	6.0



Docee River Water Temperature
Median and Quartiles for POT>19c Event Duration

Site Docee
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	0.4	1.0	0.0	0.0	0.0	0.0	3.0
	2011-2040	10	2.2	1.9	0.0	0.0	2.0	3.5	5.0
	2041-2070	10	2.8	2.3	0.0	0.0	3.5	5.0	5.5
	2071-2100	10	4.1	2.1	0.0	4.0	4.5	5.5	6.3
RCP85	1971-2000	10	0.4	1.0	0.0	0.0	0.0	0.0	3.0
	2011-2040	10	2.6	2.1	0.0	0.0	3.0	4.5	5.3
	2041-2070	10	4.2	2.2	1.5	2.3	3.7	6.6	8.1
	2071-2100	10	8.3	5.7	3.3	5.2	6.1	8.0	22.0
All		80	3.1	3.5	0.0	0.0	3.0	4.9	22.0

Table 13. Regional Air Temperature (Port Hardy; left) and Docee Water Temperature (right). Mean annual duration of continuous POT temperature events across all models and years by time-period and month.

Babine – Projected Monthly Temperature Statistics

Site: Babine
and Method: BCCAQ

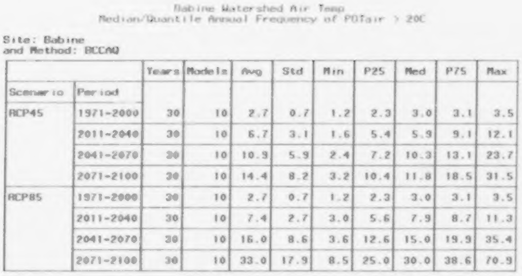
		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	12.1	3.4	14.3	3.0	13.8	3.2	9.5	3.4	11.8	3.5	14.6	2.2	15.1	1.7	12.6	1.9
	2011-2040	13.1	3.4	15.6	3.2	14.9	3.4	10.6	3.5	13.1	3.2	15.6	1.8	15.9	1.6	13.4	1.9
	2041-2070	14.1	3.6	16.5	3.2	16.0	3.5	11.5	3.5	14.1	2.9	16.2	1.5	16.5	1.5	14.0	1.9
	2071-2100	14.6	3.5	17.2	3.4	16.5	3.5	12.0	3.6	14.6	2.7	16.6	1.3	16.9	1.5	14.4	2.0
RCP85	1971-2000	12.1	3.4	14.3	3.0	13.8	3.2	9.5	3.4	11.8	3.5	14.6	2.2	15.1	1.7	12.6	1.9
	2011-2040	13.4	3.6	15.7	3.2	15.1	3.3	10.8	3.5	13.4	3.2	15.8	1.8	16.0	1.5	13.5	2.0
	2041-2070	14.7	3.6	17.5	3.5	16.7	3.7	12.1	3.6	14.7	2.7	16.7	1.3	16.9	1.5	14.5	2.0
	2071-2100	16.6	3.9	19.6	3.9	19.0	4.0	14.1	3.9	16.0	2.0	17.4	0.8	18.0	1.5	15.7	2.1

Site: Babine
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	10	12	14	12	14	16	11	14	16	7	9	12	9	12	15	13	15	16	14	15	16	11	13	14
	2011-2040	11	13	15	13	15	18	13	15	17	8	10	13	11	13	16	15	16	17	15	16	17	12	13	15
	2041-2070	12	14	16	14	16	19	13	16	18	9	11	14	12	15	16	15	17	17	16	17	18	13	14	15
	2071-2100	12	14	17	15	17	20	14	16	19	9	12	15	13	15	17	16	17	18	16	17	18	13	14	16
RCP85	1971-2000	10	12	14	12	14	16	11	14	16	7	9	12	9	12	15	13	15	16	14	15	16	11	13	14
	2011-2040	11	13	16	13	15	18	13	15	17	8	11	13	11	14	16	15	16	17	15	16	17	12	13	15
	2041-2070	12	14	17	15	17	20	14	16	19	10	12	15	13	15	17	16	17	18	16	17	18	13	14	16
	2071-2100	14	16	19	17	19	22	16	19	22	11	14	17	15	17	18	17	18	18	17	18	19	14	16	17

Table 14. Projected mean regional air (Topley Landing) and Babine River water temperature (°C) statistics (mean, standard deviation; top) and quartiles (25th, 50th, and 75th percentiles; bottom), across all GCM models by RCP, time-period and month.

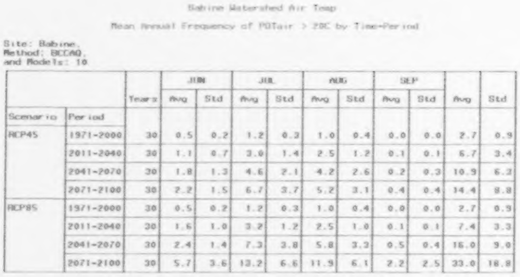
Babine Watershed - POT Frequency Tables



Babine Watershed Air Temp
Median/Quantile Annual Frequency of POTair > 20C

Site: Babine
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	2.7	0.7	1.2	2.3	3.0	3.1	3.5
	2011-2040	30	10	6.7	3.1	1.6	5.4	5.9	9.1	12.1
	2041-2070	30	10	10.9	5.9	2.4	7.2	10.3	13.1	23.7
	2071-2100	30	10	14.4	8.2	3.2	10.4	11.8	18.5	31.5
RCP85	1971-2000	30	10	2.7	0.7	1.2	2.3	3.0	3.1	3.5
	2011-2040	30	10	7.4	2.7	3.0	5.6	7.9	8.7	11.3
	2041-2070	30	10	16.0	8.6	3.6	12.6	15.0	19.9	35.4
	2071-2100	30	10	33.0	17.9	8.5	25.0	30.0	38.6	70.9

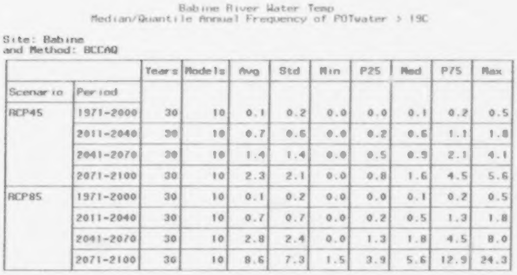


Babine Watershed Air Temp
Mean Annual Frequency of POTair > 20C by Time-Period

Site: Babine,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
Scenario	Period	Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
RCP45	1971-2000	30	0.5	0.2	1.2	0.3	1.0	0.4	0.0	0.0	2.7	0.9
	2011-2040	30	1.1	0.7	3.0	1.4	2.5	1.2	0.1	0.1	6.7	3.4
	2041-2070	30	1.8	1.3	4.6	2.1	4.2	2.6	0.2	0.3	10.9	6.2
	2071-2100	30	2.2	1.5	6.7	3.7	5.2	3.1	0.4	0.4	14.4	8.8
RCP85	1971-2000	30	0.5	0.2	1.2	0.3	1.0	0.4	0.0	0.0	2.7	0.9
	2011-2040	30	1.6	1.0	3.2	1.2	2.5	1.0	0.1	0.1	7.4	3.3
	2041-2070	30	2.4	1.4	7.3	3.8	5.8	3.3	0.5	0.4	16.0	9.0
	2071-2100	30	5.7	3.6	13.2	6.6	11.9	6.1	2.2	2.5	33.0	18.8

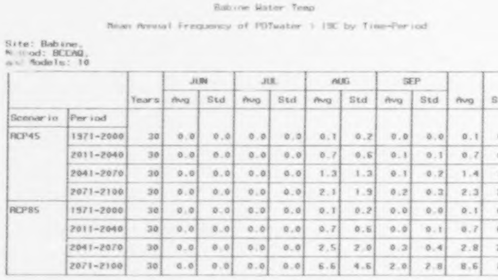
Table 15. Regional Air Temperature (Topley Landing). Mean annual frequency of POT$_{20\,^{\circ}C}$ air temperature events across all models and years by RCP, time-period and month.



Babine River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Babine
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	0.1	0.2	0.0	0.0	0.1	0.2	0.5
	2011-2040	30	10	0.7	0.6	0.0	0.2	0.6	1.1	1.8
	2041-2070	30	10	1.4	1.4	0.0	0.5	0.9	2.1	4.1
	2071-2100	30	10	2.3	2.1	0.0	0.8	1.6	4.5	5.6
RCP85	1971-2000	30	10	0.1	0.2	0.0	0.0	0.1	0.2	0.5
	2011-2040	30	10	0.7	0.7	0.0	0.2	0.5	1.3	1.8
	2041-2070	30	10	2.8	2.4	0.0	1.3	1.8	4.5	8.0
	2071-2100	30	10	8.6	7.3	1.5	3.9	5.6	12.9	24.3



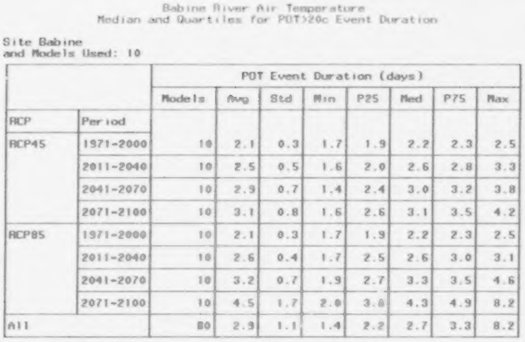
Babine Water Temp
Mean Annual Frequency of POTwater > 19C by Time-Period

Site: Babine,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
Scenario	Period	Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
RCP45	1971-2000	30	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.1	0.2
	2011-2040	30	0.0	0.0	0.0	0.0	0.7	0.6	0.1	0.1	0.7	0.7
	2041-2070	30	0.0	0.0	0.0	0.0	1.3	1.3	0.1	0.2	1.4	1.4
	2071-2100	30	0.0	0.0	0.0	0.0	2.1	1.9	0.2	0.3	2.3	2.1
RCP85	1971-2000	30	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.1	0.2
	2011-2040	30	0.0	0.0	0.0	0.0	0.7	0.6	0.0	0.1	0.7	0.7
	2041-2070	30	0.0	0.0	0.0	0.0	2.5	2.0	0.3	0.4	2.8	2.4
	2071-2100	30	0.0	0.0	0.0	0.0	6.6	4.6	2.0	2.8	8.6	7.3

Table 16. Babine River Water Temperature. Mean annual frequency of POT$_{19\,^{\circ}C}$ water temperature events across all models and years by RCP, time-period and month.

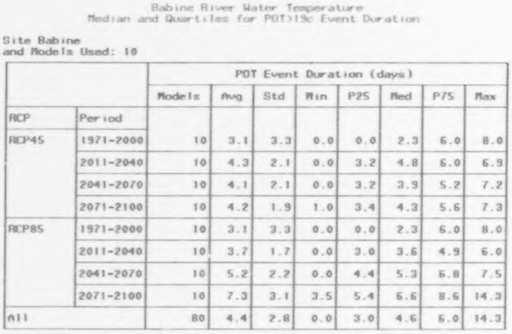
Babine Watershed - POT Duration Tables



Babine River Air Temperature
Median and Quartiles for POT>20c Event Duration

Site Babine
and Models Used: 10

		POT Event Duration (days)							
RCP	Period	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	10	2.1	0.3	1.7	1.9	2.2	2.3	2.5
	2011-2040	10	2.5	0.5	1.6	2.0	2.6	2.8	3.3
	2041-2070	10	2.9	0.7	1.4	2.4	3.0	3.2	3.8
	2071-2100	10	3.1	0.8	1.6	2.6	3.1	3.5	4.2
RCP85	1971-2000	10	2.1	0.3	1.7	1.9	2.2	2.3	2.5
	2011-2040	10	2.6	0.4	1.7	2.5	2.6	3.0	3.1
	2041-2070	10	3.2	0.7	1.9	2.7	3.3	3.5	4.6
	2071-2100	10	4.5	1.7	2.0	3.8	4.3	4.9	8.2
All		80	2.9	1.1	1.4	2.2	2.7	3.3	8.2



Babine River Water Temperature
Median and Quartiles for POT>19c Event Duration

Site Babine
and Models Used: 10

		POT Event Duration (days)							
RCP	Period	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	10	3.1	3.3	0.0	0.0	2.3	6.0	8.0
	2011-2040	10	4.3	2.1	0.0	3.2	4.8	6.0	6.9
	2041-2070	10	4.1	2.1	0.0	3.2	3.9	5.2	7.2
	2071-2100	10	4.2	1.9	1.0	3.4	4.3	5.6	7.3
RCP85	1971-2000	10	3.1	3.3	0.0	0.0	2.3	6.0	8.0
	2011-2040	10	3.7	1.7	0.0	3.0	3.6	4.9	6.0
	2041-2070	10	5.2	2.2	0.0	4.4	5.3	6.8	7.5
	2071-2100	10	7.3	3.1	3.5	5.4	6.6	8.6	14.3
All		80	4.4	2.8	0.0	3.0	4.6	6.0	14.3

Table 17. Regional Air Temperature (Topley Landing; left) and Babine Water Temperature (right). Mean annual duration of continuous POT temperature events across all models and years by time-period and month.

Meziadin Watershed – Projected Monthly Temperature Statistics

Site: Meziadin
and Method: BCCAQ

		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	13.1	2.5	14.8	2.3	14.5	2.4	11.3	2.3	12.9	2.2	14.7	1.6	15.4	1.6	12.5	1.9
	2011-2040	14.3	2.7	15.9	2.5	15.4	2.5	12.2	2.4	14.1	2.1	15.6	1.4	16.2	1.6	13.4	2.0
	2041-2070	15.3	2.8	16.7	2.5	16.3	2.5	13.1	2.4	14.9	1.9	16.1	1.2	16.8	1.3	14.2	2.0
	2071-2100	15.9	2.8	17.3	2.6	16.8	2.6	13.6	2.5	15.4	1.7	16.5	1.1	17.2	1.3	14.7	2.0
RCP85	1971-2000	13.1	2.5	14.8	2.3	14.5	2.4	11.3	2.3	12.9	2.2	14.7	1.6	15.4	1.6	12.5	1.9
	2011-2040	14.6	2.8	16.0	2.5	15.6	2.4	12.4	2.5	14.3	2.1	15.7	1.4	16.3	1.4	13.6	2.1
	2041-2070	15.9	2.9	17.5	2.7	17.0	2.7	13.6	2.5	15.4	1.8	16.5	1.2	17.2	1.3	14.8	2.0
	2071-2100	17.4	3.2	19.1	2.9	18.8	3.0	15.2	2.7	16.3	1.5	17.3	0.9	18.1	1.0	16.1	1.9

Site: Meziadin
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	11	13	15	13	15	16	13	14	16	10	11	13	11	13	15	14	15	16	14	15	17	11	12	14
	2011-2040	12	14	16	14	16	18	14	15	17	11	12	14	13	14	16	15	16	17	15	16	17	12	13	15
	2041-2070	13	15	17	15	16	18	14	16	18	11	13	15	14	15	16	15	16	17	16	17	18	13	14	16
	2071-2100	14	16	18	15	17	19	15	17	18	12	13	15	14	16	17	16	17	17	16	17	18	13	15	16
RCP85	1971-2000	11	13	15	13	15	16	13	14	16	10	11	13	11	13	15	14	15	16	14	15	17	11	12	14
	2011-2040	13	14	16	14	16	18	14	15	17	11	12	14	13	15	16	15	16	17	15	16	17	12	14	15
	2041-2070	14	16	18	15	17	19	15	17	19	12	13	15	14	16	17	16	17	17	16	17	18	13	15	16
	2071-2100	15	17	20	17	19	21	17	18	21	13	15	17	15	17	18	17	17	18	17	18	19	15	16	18

Table 18. Projected mean regional air (Stewart) and Meziadin River water temperature (°C) statistics (mean, standard deviation; top) and quartiles (25th, 50th, and 75th percentiles; bottom), across all GCM models by RCP, time-period and month.

Meziadin Watershed - POT Frequency Tables

Meziadin Watershed Air Temp
Median/Quantile Annual Frequency of POTair > 20C

Site: Meziadin
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	1.5	0.4	0.5	1.6	1.6	1.7	2.0
	2011-2040	30	10	4.6	2.6	1.2	3.2	4.4	5.4	10.5
	2041-2070	30	10	8.0	5.2	1.2	5.0	6.9	11.8	18.9
	2071-2100	30	10	11.6	6.9	1.5	6.7	11.2	14.8	26.0
RCP85	1971-2000	30	10	1.5	0.4	0.5	1.5	1.6	1.7	2.0
	2011-2040	30	10	5.2	2.5	1.4	3.6	5.7	6.8	9.3
	2041-2070	30	10	12.9	8.1	1.9	8.5	12.5	14.5	31.4
	2071-2100	30	10	29.0	17.5	5.8	19.5	26.1	38.3	67.3

Meziadin Watershed Air Temp

Mean Annual Frequency of POTair > 20C by Time-Period

Site: Meziadin,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.3	0.2	0.6	0.2	0.6	0.3	0.0	0.0	1.5	0.7
	2011-2040	30	0.9	0.8	2.0	1.2	1.6	1.0	0.1	0.1	4.6	3.1
	2041-2070	30	1.8	1.8	3.4	1.8	2.7	2.2	0.1	0.1	8.0	5.9
	2071-2100	30	2.6	2.4	5.0	3.1	3.7	2.6	0.3	0.2	11.6	8.3
RCP85	1971-2000	30	0.3	0.2	0.6	0.2	0.6	0.3	0.0	0.0	1.5	0.7
	2011-2040	30	1.2	1.0	2.3	1.0	1.6	0.8	0.1	0.1	5.2	2.9
	2041-2070	30	2.6	2.3	5.7	3.5	4.4	3.0	0.3	0.3	12.9	9.2
	2071-2100	30	6.4	5.2	11.1	6.2	9.9	5.7	1.7	2.1	29.0	19.1

Table 19. Regional Air Temperature (Stewart). Mean annual frequency of POT$_{20\ ^\circ C}$ air temperature events across all models and years by RCP, time-period and month.

Meziadin River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Meziadin
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	0.1	0.1	0.0	0.0	0.0	0.1	0.4
	2011-2040	30	10	0.4	0.4	0.0	0.1	0.2	0.8	1.1
	2041-2070	30	10	0.7	1.0	0.0	0.1	0.3	0.8	2.9
	2071-2100	30	10	1.5	1.6	0.0	0.2	1.2	2.2	4.9
RCP85	1971-2000	30	10	0.1	0.1	0.0	0.0	0.0	0.1	0.4
	2011-2040	30	10	0.5	0.5	0.0	0.2	0.4	0.5	1.8
	2041-2070	30	10	1.8	2.0	0.0	0.5	1.1	3.0	6.7
	2071-2100	30	10	7.0	6.4	0.8	2.8	5.0	8.6	22.8

Meziadin Water Temp

Mean Annual Frequency of POTwater > 19C by Time-Period

Site: Meziadin,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
	2011-2040	30	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.4	0.4
	2041-2070	30	0.0	0.0	0.0	0.0	0.7	1.0	0.0	0.1	0.7	1.0
	2071-2100	30	0.0	0.0	0.0	0.0	1.5	1.5	0.1	0.1	1.5	1.7
RCP85	1971-2000	30	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
	2011-2040	30	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.5	0.5
	2041-2070	30	0.0	0.0	0.0	0.0	1.8	1.9	0.1	0.1	1.8	2.0
	2071-2100	30	0.0	0.0	0.0	0.0	6.1	4.9	0.9	1.5	7.0	6.4

Table 20. Meziadin River Water Temperature. Mean annual frequency of POT$_{19\ ^\circ C}$ water temperature events across all models and years by RCP, time-period and month.

Meziadin Watershed - POT Duration Tables

Meziadin River Air Temperature
Median and Quartiles for POT>20c Event Duration

Site Meziadin
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	2.0	0.4	1.2	1.8	2.0	2.1	2.9
	2011-2040	10	2.3	0.4	1.7	2.2	2.3	2.6	2.8
	2041-2070	10	2.7	0.6	1.2	2.5	2.8	3.2	3.5
	2071-2100	10	2.8	0.7	1.2	2.5	2.9	3.2	3.8
RCP85	1971-2000	10	2.0	0.4	1.2	1.8	2.0	2.1	2.9
	2011-2040	10	2.6	0.4	2.0	2.5	2.6	2.8	3.2
	2041-2070	10	3.1	0.8	1.4	2.7	3.2	3.5	4.3
	2071-2100	10	4.1	1.2	2.4	3.5	3.9	4.4	7.0
All		80	2.7	0.9	1.2	2.1	2.6	3.2	7.0

Meziadin River Water Temperature
Median and Quartiles for POT>19c Event Duration

Site Meziadin
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	1.5	2.2	0.0	0.0	0.5	2.0	6.0
	2011-2040	10	3.1	1.6	0.0	2.0	3.6	4.3	4.7
	2041-2070	10	3.0	1.5	0.0	2.0	3.3	4.0	5.4
	2071-2100	10	4.9	2.6	0.0	3.5	5.2	6.7	8.6
RCP85	1971-2000	10	1.5	2.2	0.0	0.0	0.5	2.0	6.0
	2011-2040	10	5.0	4.1	0.0	2.5	4.8	7.0	14.0
	2041-2070	10	4.5	2.5	0.0	3.0	4.1	7.0	8.2
	2071-2100	10	7.4	2.6	4.2	5.8	7.0	8.3	13.7
All		80	3.9	3.0	0.0	1.3	3.9	5.9	14.0

Table 21. Regional Air Temperature (Stewart; left) and Meziadin Water Temperature (right). Mean annual duration of continuous POT temperature events across all models and years by time-period and month.

Tahltan Watershed – Projected Monthly Temperature Statistics

Site: Tahltan
and Method: BCCAQ

		Daily Mean Air Temp								Daily Mean Water Temp							
		JUN		JUL		AUG		SEP		JUN		JUL		AUG		SEP	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Scenario	Period																
RCP45	1971-2000	10.9	3.3	12.9	2.9	11.8	3.3	7.2	3.4	11.9	2.9	14.2	2.3	15.4	1.6	12.2	2.0
	2011-2040	12.2	3.4	14.1	3.1	12.9	3.4	8.4	3.5	13.2	2.9	15.3	2.2	16.0	1.5	13.0	2.0
	2041-2070	13.2	3.6	14.9	3.1	13.8	3.4	9.3	3.4	14.2	2.9	16.0	2.0	16.5	1.4	13.7	1.9
	2071-2100	13.9	3.5	15.6	3.1	14.4	3.4	9.8	3.6	14.9	2.7	16.5	1.9	16.8	1.4	14.0	2.0
RCP85	1971-2000	10.9	3.3	12.9	2.9	11.8	3.3	7.2	3.4	11.9	2.9	14.2	2.3	15.4	1.6	12.2	2.0
	2011-2040	12.4	3.5	14.1	3.0	13.0	3.3	8.5	3.5	13.5	3.0	15.4	2.1	16.0	1.4	13.1	2.0
	2041-2070	13.9	3.7	15.7	3.3	14.6	3.5	9.9	3.5	14.9	2.8	16.6	2.0	16.8	1.4	14.1	1.9
	2071-2100	15.8	4.0	17.5	3.5	16.6	3.7	11.8	3.8	16.4	2.5	17.7	1.7	17.7	1.2	15.2	1.9

Site: Tahltan
and Method: BCCAQ

		Daily Mean Air Temp												Daily Mean Water Temp											
		JUN			JUL			AUG			SEP			JUN			JUL			AUG			SEP		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Scenario	Period																								
RCP45	1971-2000	8	11	13	11	13	15	10	12	14	5	7	9	10	12	14	13	14	16	14	15	16	11	12	14
	2011-2040	10	12	14	12	14	16	10	13	15	6	8	11	11	13	15	14	15	17	15	16	17	12	13	14
	2041-2070	11	13	16	13	15	17	12	14	16	7	9	12	12	14	16	15	16	17	16	17	17	12	14	15
	2071-2100	11	14	16	13	15	18	12	14	17	7	10	12	13	15	17	15	17	18	16	17	18	13	14	15
RCP85	1971-2000	8	11	13	11	13	15	10	12	14	5	7	9	10	12	14	13	14	16	14	15	16	11	12	14
	2011-2040	10	12	15	12	14	16	11	13	15	6	8	11	11	14	16	14	15	17	15	16	17	12	13	15
	2041-2070	11	14	16	13	16	18	12	14	17	8	10	12	13	15	17	15	17	18	16	17	18	13	14	15
	2071-2100	13	16	19	15	17	20	14	16	19	9	12	14	15	17	18	17	18	19	17	18	19	14	15	17

Table 22. Projected mean regional air (Dease Lake) and Tahltan River water temperature (°C) statistics (mean, standard deviation; top) and quartiles (25th, 50th, and 75th percentiles; bottom), across all GCM models by RCP, time-period and month.

Tahltan Watershed - POT Frequency Tables

Tahltan Watershed Air Temp
Median/Quantile Annual Frequency of POTair > 20C

Site: Tahltan
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	0.6	0.2	0.2	0.3	0.7	0.7	0.8
	2011-2040	30	10	2.3	1.4	0.2	1.8	1.9	3.3	5.2
	2041-2070	30	10	4.5	3.1	0.3	2.8	3.9	5.9	11.6
	2071-2100	30	10	6.0	4.1	0.2	3.2	6.0	7.3	15.4
RCP85	1971-2000	30	10	0.6	0.2	0.2	0.3	0.7	0.7	0.8
	2011-2040	30	10	2.4	1.4	0.4	1.8	2.4	3.3	4.3
	2041-2070	30	10	7.2	5.4	0.5	4.2	7.1	7.8	20.9
	2071-2100	30	10	18.7	12.2	1.7	13.9	18.5	22.3	46.8

Tahltan Watershed Air Temp
Mean Annual Frequency of POTair > 20C by Time-Period

Site: Tahltan,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.1	0.1	0.2	0.1	0.3	0.2	0.0	0.0	0.6	0.4
	2011-2040	30	0.5	0.4	0.9	0.8	0.8	0.5	0.0	0.1	2.3	1.8
	2041-2070	30	1.1	1.1	1.8	1.3	1.5	1.1	0.1	0.2	4.5	3.7
	2071-2100	30	1.2	1.1	2.3	1.9	2.1	1.5	0.4	0.8	6.0	5.3
RCP85	1971-2000	30	0.1	0.1	0.2	0.1	0.3	0.2	0.0	0.0	0.6	0.4
	2011-2040	30	0.5	0.5	0.9	0.6	0.9	0.6	0.1	0.2	2.4	1.9
	2041-2070	30	1.5	1.5	3.1	2.6	2.4	1.9	0.2	0.4	7.2	6.3
	2071-2100	30	4.3	4.3	6.6	4.4	6.6	4.2	1.2	1.6	18.7	14.5

Table 23. Regional Air Temperature (Dease Lake). Mean annual frequency of POT$_{20\ ^{\circ}\mathrm{C}}$ air temperature events across all models and years by RCP, time-period and month.

Tahltan River Water Temp
Median/Quantile Annual Frequency of POTwater > 19C

Site: Tahltan
and Method: BCCAQ

Scenario	Period	Years	Models	Avg	Std	Min	P25	Med	P75	Max
RCP45	1971-2000	30	10	0.2	0.2	0.0	0.0	0.2	0.3	0.5
	2011-2040	30	10	1.4	1.2	0.0	0.5	1.2	2.2	3.9
	2041-2070	30	10	3.1	2.9	0.0	1.5	2.3	4.4	10.2
	2071-2100	30	10	4.8	4.2	0.0	1.8	4.3	6.0	15.1
RCP85	1971-2000	30	10	0.2	0.2	0.0	0.0	0.2	0.3	0.5
	2011-2040	30	10	1.6	1.1	0.1	1.0	1.5	2.2	3.4
	2041-2070	30	10	5.8	5.6	0.1	3.0	5.0	6.5	20.5
	2071-2100	30	10	17.6	13.7	0.6	10.9	16.5	22.4	50.2

Tahltan Water Temp
Mean Annual Frequency of POTwater > 19C by Time-Period

Site: Tahltan,
Method: BCCAQ,
and Models: 10

			JUN		JUL		AUG		SEP			
		Years	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Scenario	Period											
RCP45	1971-2000	30	0.0	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.2	0.3
	2011-2040	30	0.3	0.4	0.7	0.7	0.3	0.3	0.0	0.0	1.4	1.4
	2041-2070	30	0.9	1.2	1.4	1.3	0.7	0.8	0.0	0.1	3.1	3.3
	2071-2100	30	1.0	1.1	2.2	2.1	1.4	1.5	0.2	0.4	4.8	5.1
RCP85	1971-2000	30	0.0	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.2	0.3
	2011-2040	30	0.4	0.4	0.7	0.5	0.4	0.5	0.0	0.1	1.6	1.5
	2041-2070	30	1.4	1.5	2.8	3.0	1.5	1.7	0.1	0.3	5.8	6.5
	2071-2100	30	4.4	4.8	6.9	5.5	5.5	4.5	0.8	1.3	17.6	16.1

Table 24. Tahltan River Water Temperature. Mean annual frequency of POT$_{19\ ^{\circ}\mathrm{C}}$ water temperature events across all models and years by RCP, time-period and month.

Tahltan Watershed - POT Duration Tables

Tahltan River Air Temperature
Median and Quartiles for POT>20c Event Duration

Site Tahltan
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	1.8	0.5	1.2	1.3	1.9	2.2	2.6
	2011-2040	10	2.1	0.5	1.0	1.8	2.1	2.4	2.8
	2041-2070	10	2.5	0.5	1.3	2.4	2.6	2.8	3.1
	2071-2100	10	2.6	0.6	1.2	2.3	2.8	2.9	3.2
RCP85	1971-2000	10	1.8	0.5	1.2	1.3	1.9	2.2	2.6
	2011-2040	10	2.1	0.6	1.3	1.7	2.2	2.4	3.4
	2041-2070	10	2.6	0.6	1.4	2.3	2.6	2.9	3.4
	2071-2100	10	3.4	0.9	1.7	3.1	3.4	3.8	5.3
All		80	2.4	0.8	1.0	1.9	2.4	2.8	5.3

Tahltan River Water Temperature
Median and Quartiles for POT>19c Event Duration

Site Tahltan
and Models Used: 10

		POT Event Duration (days)							
		Models	Avg	Std	Min	P25	Med	P75	Max
RCP	Period								
RCP45	1971-2000	10	2.3	1.9	0.0	0.0	2.8	3.7	5.3
	2011-2040	10	4.4	2.4	0.0	2.7	4.9	5.8	7.3
	2041-2070	10	5.2	2.6	0.0	4.4	5.1	5.9	9.5
	2071-2100	10	5.7	2.6	0.0	4.0	6.2	7.5	8.9
RCP85	1971-2000	10	2.3	1.9	0.0	0.0	2.8	3.7	5.3
	2011-2040	10	4.8	1.4	2.0	4.6	5.1	5.5	7.3
	2041-2070	10	6.6	2.2	3.0	5.1	6.1	8.2	9.6
	2071-2100	10	8.8	3.3	3.8	8.5	8.6	9.7	16.2
All		80	5.0	3.0	0.0	3.2	5.0	7.2	16.2

Table 25. Regional Air Temperature (Dease Lake; left) and Tahltan Water Temperature (right). Mean annual duration of continuous POT temperature events across all models and years by time-period and month.